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Preliminary Report

SPACE SHUTTLE ELECTROMAGNETIC ENVIRONMENT EXPERIMENT

Phase A: Definition Study

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Greenbelt, Maryland 20771

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16. Abstract

The report reviews the initial effort on a program to develop a concept for measuring the electromagnetic environment on earth with equipment on board an orbiting space shuttle. Earlier work on space-borne measuring experiments is reviewed and emissions to be expected are estimated using, in part, previously gathered data. General relations among system parameters are presented, followed by a proposal on spatial and frequency scanning concepts. The methods proposed include a nadir looking measurement with small lateral scan and a circularly scanned measurement looking tangent to the earth's surface at the horizon. Antenna requirements are given, assuming frequency coverage from 400 MHz to 40 GHz. For the low frequency range, 400-1000 MHz, a processed, thinned array is proposed which will be more fully analyzed in the next phase of the program. Preliminary hardware and data processing requirements are presented. The report concludes with a summary of the work to be done during the next phase.

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ABSTRACT

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1.0 INTRODUCTION

1.1 Objective and Background Information

The work reported herein is the initial effort on a contract with NASA Goddard Space Flight Center on "Validation and Specification for a Space Shuttle RFI Experiment". The main objective is to develop a plan for a comprehensive measuring system capable of systematically surveying electromagnetic emissions from the earth, and suitable for accommodation on the space shuttle.

The initial phase of the work has been directed toward: (a) a review of past efforts at the measurement and estimation of fields in space; and (b) establishing an appropriate concept. It has advanced to the point where a methodology can be proposed.

The use of satellites for surveying electromagnetic emissions from the earth's surface has been under discussion for about 10 years [1-6] and, indeed, a number of measurements have been and are being made [7-11]. The experiments actually carried out have been of a restricted nature designed either to demonstrate the feasibility of such measurements or to obtain a specific kind of information. The Space Shuttle Electromagnetic Environment Experiment (EEE) is intended to provide more comprehensive results and, where it is advantageous, to make use of the crew members in carrying out measurements.

In designing the experiment, it is essential to determine who will be principal users of the data. A recent paper by R.E. Taylor, R. E. Prince, and D. N. McGregor [12] lists national and international bodies concerned with spectrum use and management, as well as NASA itself. Accordingly, the measurement methods proposed here have in mind various possible users. Principally, however, the orientation of this work is to applications in space. Space systems see wide areas of earth. In a recent article surveying the state of domestic satellites [13] it is pointed out that interference problems associated with the satellite-to-earth link are not usually important, since control can be exercised through proper siting of the ground station.* The satellite, however (in the case under discussion synchronous satellites were in mind), is subject to interference from widely dispersed points, so that proper choice of the earth-to-satellite frequency is important. Emissions from ground-based sources affecting satellite operations can be categorized as follows: intentional emissions whose fundamental frequencies lie in or close to the bands allocated for satellite operations; intentional emissions whose fundamental frequencies are not in those bands but whose harmonics or spurious emissions are; and unintentional emissions that may come from ignition systems, Industrial, Scientific, and Medical (ISM) equipment, welding equipment, or hitherto unsuspected sources.

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* An exception is down link commands to data collection balloons (SMS geostationary satellite).

There are three principal ways to obtain information about some of these emissions: (1) by examination and correlation of data on emitters listed by such agencies as the Electromagnetic Compatibility Analysis Center (ECAC) and the Federal Communications Commission (FCC); (2) by direct measurement with ground-based or aircraft-based monitoring equipment; (3) by direct measurement from a satellite.

Other investigators [14] have concluded that the first approach is of limited value in large part because files do not include actual use of licensed devices. A satellite-based system would update emitters not yet listed in the files, and it would also give much needed information on unintentional and spurious emitters.

A satellite-borne monitor offers the potential to pinpoint hitherto unsuspected RFI sources, and could directly examine the RFI environment as it would be seen by subsequent satellites. While it would be impossible for a satellite monitor in a low earth orbit to continuously monitor single sources for prolonged periods, it could examine such sources for short periods at different times of day, and from different angles, and it might identify sources that are worthy of more intensive examination by ground-based or airborne monitors. Two satellites, the LES-5 and LES-6, have monitored portions of the spectrum from 255 to 280 and from 290 to 315 MHz. The ATS-6 geo-stationary satellite is now making measurements in the vicinity of 6 GHz.* Except for this, none have investigated the many bands reserved for earth-satellite communications in the 0.4-40 GHz range and none have provided high geographic resolution. A cost/benefit study [14] has indicated that a survey of these bands would improve the performance of subsequent missions, particularly space shuttle missions.

The University of Pennsylvania effort is being carried out with attention to the following steps:

1. Examinations of the expected environment, including the numbers, types, and intensities of emitters as seen at the satellite

2. Choice of a measuring concept which will supply the information required by users

3. Consideration of the possibilities of supplying the information by alternate means

4. Analysis of the technical parameters of possible measurements conducted from an orbiting vehicle at the expected altitude. This will include a trade-off analysis accounting for such factors as sensitivity, area coverage, and detection probability.

5. Optimum parameter selection

6. Examinations of hardware feasibility including the antenna, RF components, frequency sweep systems, and data recording and display systems (hardware implementation is to be carried out elsewhere)

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* An experiment has recently been proposed by the NASA Communication and Navigation Division to measure radio frequency interference (RFI) in the vicinity of 1.6 and 2.25 GHz using the ATS-6 satellite at synchronous altitude.

7. Data processing in the satellite and on the ground, and programming for access to the stored data

8. Consideration of how the measurements are to be distributed over the several space-shuttle missions and whether or not future continuing measurements are worthwhile.

In section 1.2 following, a discussion is presented enumerating the possible measurables, the constraints imposed by the nature of the satellite vehicle, and the expected limits of the measurements obtained. Section 2 contains a survey of data available from experiments and estimating analyses done to date, giving levels in space and numbers of emitters in specified services known to be assigned in various frequency ranges. Section 3 contains the experimental proposal as envisioned at this writing, giving the concept proposed and its justification along with a spectral and spatial coverage analysis. Details of the hardware implementation and questions of data storage, transmission, processing, retrieval, etc., have yet to be dealt with and are only briefly treated. Section 4 summarizes the results to date and indicates what remains to be done.

1.2 Measurables and System Capabilities

As pointed out earlier, the notion of making EE measurements on a space platform has been under consideration for some time. Most of these proposals include an enumeration of desirable measurables. The 1967 study by General Dynamics [15] gives the following as the output of an ideal experiment:

1. Exact location of every transmitter on earth
2. Its frequency
3. Power radiated
4. Antenna pattern and polarization
5. Transmitter modulation and duty cycle
6. Whether the transmitter is stationary, rotating, or mobile
7. Variations of transmitter output
8. Probability that a mobile transmitter is in a specific location
To these we may add:
9. Probability that a known transmitter is transmitting at a given time

The list is drawn up with the idea that only intentional transmissions need to be measured. Tests with aircraft carried out by Lincoln Laboratories [16] showed that when an area of more than three miles across is viewed (their measurements were made at frequencies between 200 and 400 MHz) the urban noise field observed has the characteristics of Gaussian random noise when intentional emitters are eliminated from the data. The receiver sees many many minute noncoherent sources simultaneously, the effect of which is an increase in the receiver noise level.

Intentional communication channels are deliberately spread out spectrally, spatially, and/or temporally to avoid interference among them. One would like the space-borne measuring system to be sufficiently

discriminating so as to identify individual intentional emitters. This does not imply that every transmitter will be detected by the measuring system. Factors affecting the probability of detection are transmitter on time, antenna directivity, power output, shuttle/ spacelab orbit, etc. These factors can be taken into account in estimating the probability that a given transmitter will be detected. Clearly, if measurements are made over a sufficiently long time, every emitter with enough power in the area surveyed will ultimately be observed.

2.0 SURVEY OF AIRCRAFT ELECTROMAGNETIC ENVIRONMENT MEASUREMENTS

For the purpose of this survey, electromagnetic radiation has been divided into two groups: that arising from intentional emitters and unintentional emitters generating coherent RF energy, and that arising from multiple natural or man-made noncoherent sources (incidental broadband emitters). A limited number of coherent and noncoherent emission measurements have been made using both airborne and spaceborne platforms. Measurements of noncoherent emissions avoided frequencies at which there were intentional sources. Measurements of coherent emissions were actually composite surveys – surveys of total radio frequency radiation measured continuously over a frequency band. In these cases, the apparent baseline radiation was treated as the noncoherent radiation component with the amplitude salients treated as coherent radiation. Because the measured data are limited, estimated information on the numbers of major sources in various services, locations, and frequencies has been assembled.

2.1 Accidental Emissions

Noncoherent noise radiation from cities at UHF frequencies has been modeled by Ploussios [16] on the basis of aircraft based surveys at 226.2 MHz, 305.5 MHz, and 369.2 MHz made over 7 cities in the Eastern United States; Miami, Jacksonville, Orlando, Baltimore, Philadelphia, New York City (Manhattan and Brooklyn), and Boston. It was noted that above 5,000 ft. where more than 3 square miles were observed, urban spectra cease to appear to originate from discrete sources, and approach random noise. The measurements are reported in terms of antenna temperature and shown in Table 1.

Table 1. Noise Temperature Recorded on C-131 Over Eastern U.S. Cities

City	Altitude		Antenna Temperature (K)		
		(Ft.)	226.2 MHz	305.5 MHz	369.2 MHz
Boston		8k	22,000	8,000	*
Baltimore		18k	23,000	7,000	*
Jacksonville		14k	14,000	3,400	*
Miami	(Cold)	18k	14,000	4,600	*
	(Hot)	10k-18k	27,000	10,500	*
Orlando		9k	9,000	4,000	2,200
Philadelphia		8k-18k	26,000	9,000	6,000
Brooklyn		8k-18k	60,000	19,000	9,500
Manhattan		8k-18k	75,000	30,000	16,000

* Accurate values not obtained due to ground RFI

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Measurements were made using total power radiometers having a 1.? MHz bandwidth and a 2 ms integration time. The antenna was a 2 dipole array matched at the three frequencies to a VSWR of less than 1.5:1.

The half power beamwidths of the antenna ranged from 42° to 112°.

Two measurements are reported for Miami, showing a significant difference between temperatures during the tourist season (hot) and the "off" season (cold). Ploussios observed that the brightness temperatures of different cities are not substantially different, excepting New York. A plot of brightness temperature profile of Philadelphia is shown in Fig. 1. From his findings, Ploussios modeled a city as an aperture having the dimension of the city within which are random sources having a uniform power density as shown in Fig. 2. The power density was found to range from 3×10^{-18} (W/m^2) Hz to 1×10^{-18} (W/m^2)/Hz over the UHF band during week days. However, New York City has a level from 5 to 6 dB higher.

A series of surveys of urban, suburban, and rural man-made incidental noise in the UHF frequency range was made by Mills [17,18] and analyzed by Anzic [19-22]. The sites surveyed were: Cleveland, where noise was measured on the ground at 480 MHz and 950 MHz; Phoenix, where noise was measured on the ground and from an aircraft near 0.3 GHz, 1.0 GHz, and 3.0 GHz; and Akron, where noise was measured from an aircraft, also at 0.3 GHz, 1.0 GHz, and 3.0 GHz. Only the results of the aircraft based surveys are presented here since, as Ploussios concluded, these are more representative of vertically propagated noise.

The Phoenix survey was conducted using receivers having a bandwidth of 2.7 MHz, and noise figures less than 4 dB. The antenna characteristics are shown below:

Table 2.   Antenna Characteristics

Freq. GHz	Type	Polarization	Gain	Half power Beamwidth	Front to back ratio-greater than
0.03	Quad Dipole	circular	11.2 dB	48°	19 dB
1	Helical	circular	11 dB	$34^{\circ} \times 47^{\circ}$	18 dB
3	Helical	circular	13 dB	$33^{\circ} \times 26^{\circ}$	20 dB

Measurements were made only on weekdays, and in the morning, at noon, and in the evening, from an altitude of 1000 and 4000 ft. at a speed of 100 ± 10 knots. The parameters measured were rms noise voltage and average noise envelope voltage.
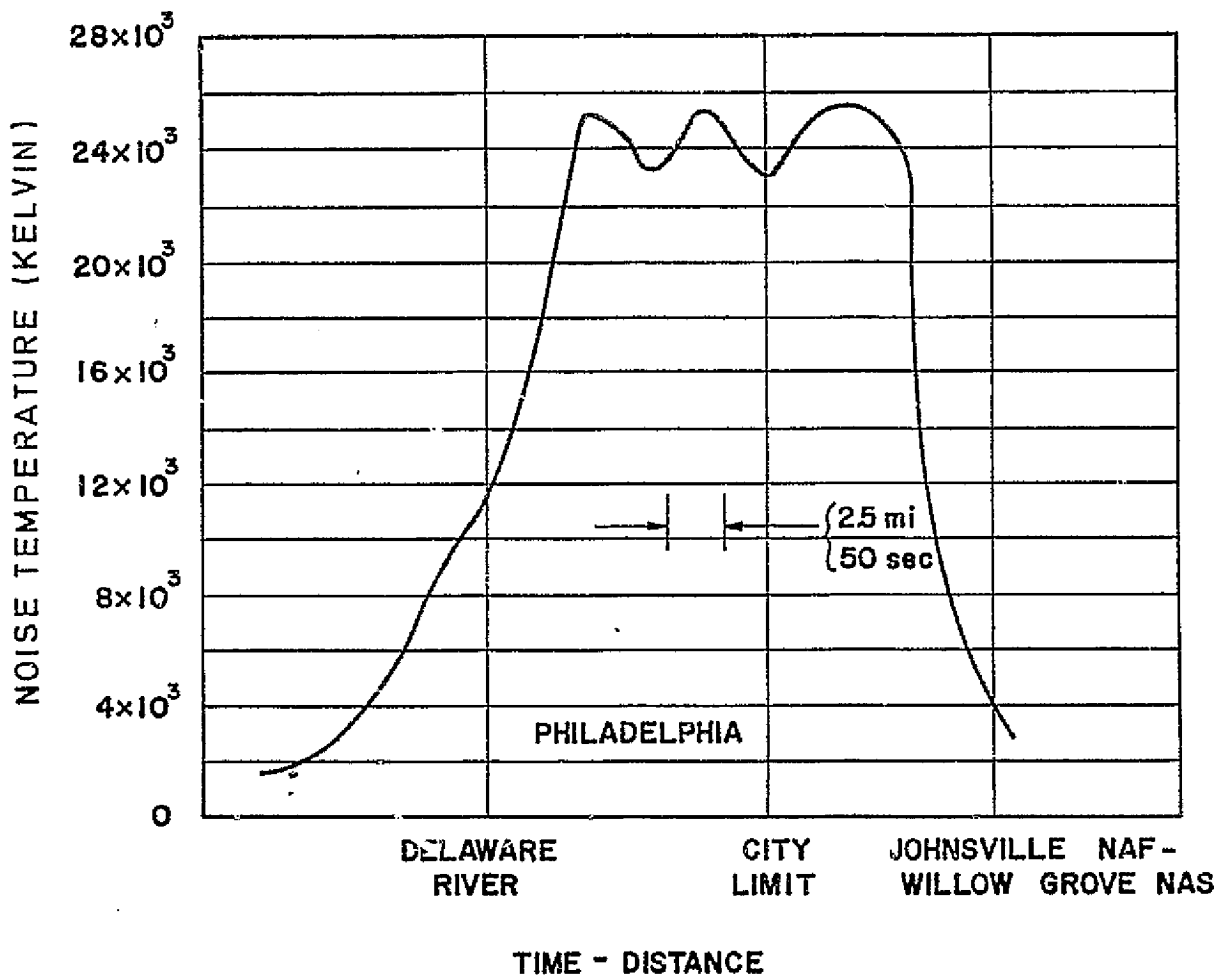
Fig. 1   Temperature Profile of Philadelphia at 226.2 MHz,
Measured Traveling North at 18,000 ft, 18 Nov. 1965
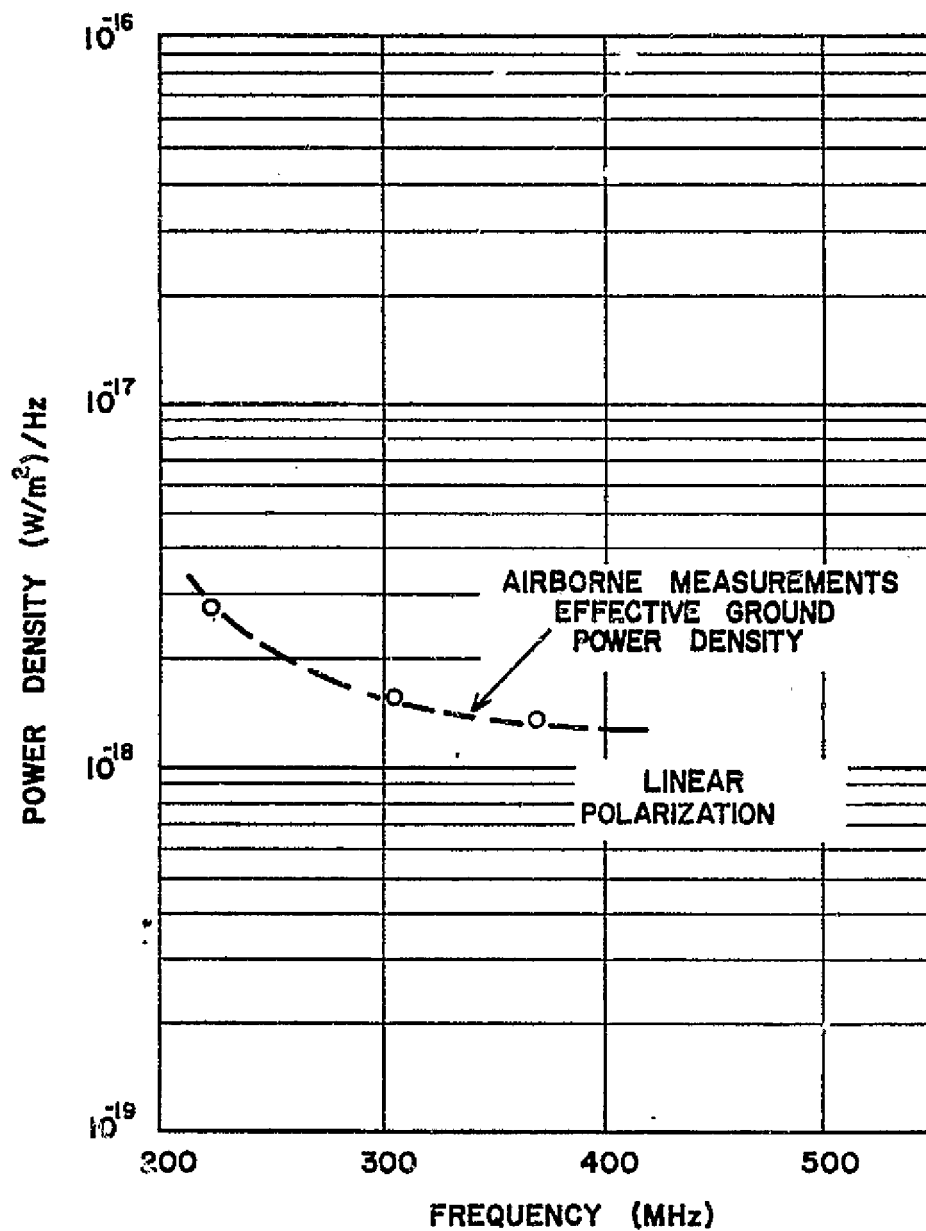(from Ref. 16).

Fig. 2   Effective Noise Power Density as Measured
in Aircraft over a City (from Ref. 16).

Data were reported in terms of dB above kTB. Average noise levels were observed to vary in a daily pattern as shown in Table 3.

Table 3. Daily Variation of Noise Levels Over Phoenix

Time of Measurement	Average level 0.3 GHz at 4000 feet * (dB above kTB)
Morning	19
Noon	17
Late Evening	13

Typical 1.0 GHz noise levels measured during morning rush hour were 5 to 6 dB below those measured at 0.3 GHz. Rms noise profiles of Phoenix, prepared from measurements made at 0.3 and 1.0 GHz during morning, noon, and evening flights, are shown in Fig. 3. The profile shown in Fig. 3a is along an east-west path crossing the city hub, while Fig. 3b shows the profile made along a north-south profile, also crossing the city hub. It is noted that the levels measured at 1.0 GHz show little variation from place to place in the city, but do show a variation of about 10 dB at different times of day. The evening profile at 0.3 GHz, made at 2119 hr, similarly is relatively flat, while a considerable variation is seen in profiles made at 0653, 0817 and 1115. No results were reported at 3.0 GHz since most data obtained were found to be unreliable because of receiver limitations. The data indicated that the RF noise level was near the system threshold most of the time (4 dB above kTB).

Measurements were made over Akron at 0.3 GHz, 1.0 GHz, and 3.0 GHz using the same equipment that was used in Phoenix, somewhat modified to take into account experience gained there. As in the Phoenix survey, the rms level measured at 3.0 GHz remained near or below the receiving system threshold, less than 4 dB above kTB, and no significant data were gathered.

The noise levels at 1.0 GHz were found to range from about 7 dB above kTB to below 4 dB above kTB, the receiving system theshold, with the exception of one narrow salient of about 20 dB above kTB, which appears on one of the profiles. The received noise level remained above the receiver threshold in urban areas and for the most part in suburban areas, while remaining below the receiver threshold most of the time in rural areas.

* Levels noted include internal noise of measuring system = 4dB above kTB
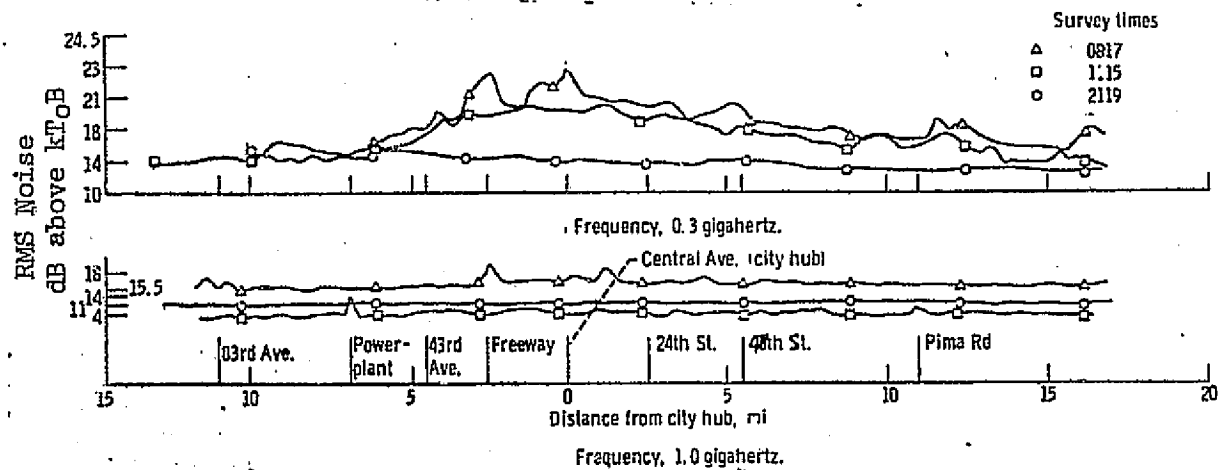
a. East-West Flight Path
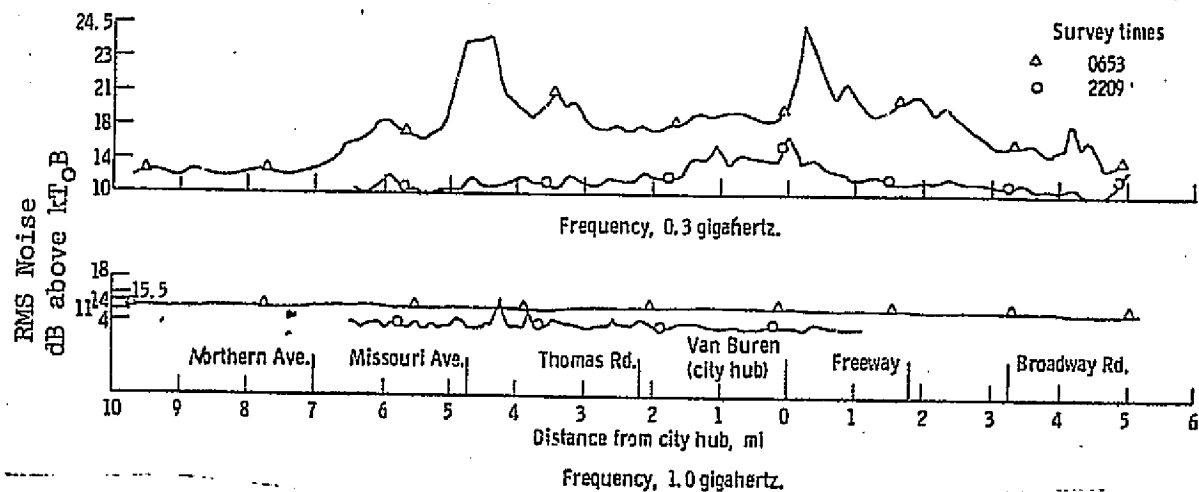
b. North-South Flight Path

Figure 3. Noise Level Variations Over Phoenix (from Ref. 19).

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The noise levels at 0.3 GHz were, as expected, substantially higher than those measured at 1.0 GHz. The measurements range from a high of about 37 dB above kTB to a low of less than 10 dB above kTB, the lower measurement appearing on one of the profiles in an area indicated as rural. Within the urban/suburban areas, the levels remained above 20 dB above kTB. A sample profile is shown in Fig. 4.

Aircraft based surveys were also performed by Barnard [23] and Buehler, King, and Lunden [24]. Barnard surveyed cities in the United Kingdom including London, Birmingham, Manchester, and Liverpool, but only at VHF frequencies, 118 MHz. Buehler et.al., surveyed Seattle, again at VHF frequencies, measuring urban, suburban, and rural radio-frequency noise at 49, 73, and 137 MHz.

Skomal [25,26] has analyzed the results of these surveys, with emphasis on the prediction of noise level depending on altitude and frequency. He notes that at altitudes above 1 mile over metropolitan areas, the impulsive character of surface incidental noise disappears and is replaced by the noise patterns which appear similar to thermal noise, eg. Gaussian. Since these surveys were not in the UHF band, they will not be further discussed.

Aircraft based surveys of composite noise covering extended geographical areas were conducted by Zamites and Hurlbut [27]. The receiver measured average and peak power in the frequency bands from 233 to 258 MHz and 290 to 315 MHz. The reported measurements are averages of those recorded along extended strips such as from Cape Cod to Dayton (Fig. 5), the Mideast, Europe, and the Eastern United States (Fig. 6). Measurements which were made in Vietnam and Southeast Asia, showed very high levels of emissions, probably due to the war. The baseline of the plot of the noise density averaged, over the Eastern United States, the Mideast, and Europe ranges between -120 dBm/kHz, and what appears to be the system noise density, about -125 dBm/kHz. Noise levels tended to reside in the lower end of this range much of the time, and fell below this level over significant parts of the spectrum surveyed, especially in the range 290 to 315 MHz. This set of surveys also included data concerning maximum and mean peak levels. The baseline of the maximum peak level plot, 290 to 315 MHz, ranges from about -70 dBm/kHz to about -90 dBm/kHz, in the average of noise observed in the Mideast, Europe, and Eastern United States. These high peak levels may be the result of coherent sources being found in such large number over the large geographical areas surveyed to take on the nature of continuous spectra, as occurred with city incidental noise sources when a sufficiently large area was viewed. The baseline of maximum peak levels, 233 to 258 MHz, observed in the Mideast, Europe, and Eastern United States ranges from -70 dBm/kHz to about -95 dBm/kHz.

Noise power and occupancy was measured by Madison, Kuehn , and Bode [28] in the frequency band 100 MHz through 500 MHz over Northern Europe, including Northeastern France, Central West Germany, Belgium, The Netherlands, and Luxemburg. The results presented are averages over this
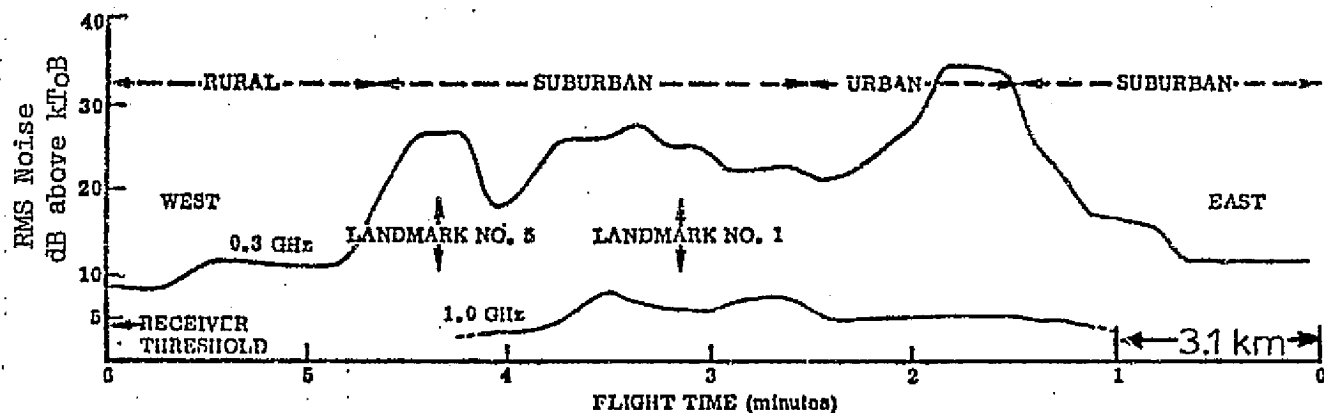
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Figure 4. Noise Level Variations on Flight Path over Akron, Ohio (from Ref. 18).
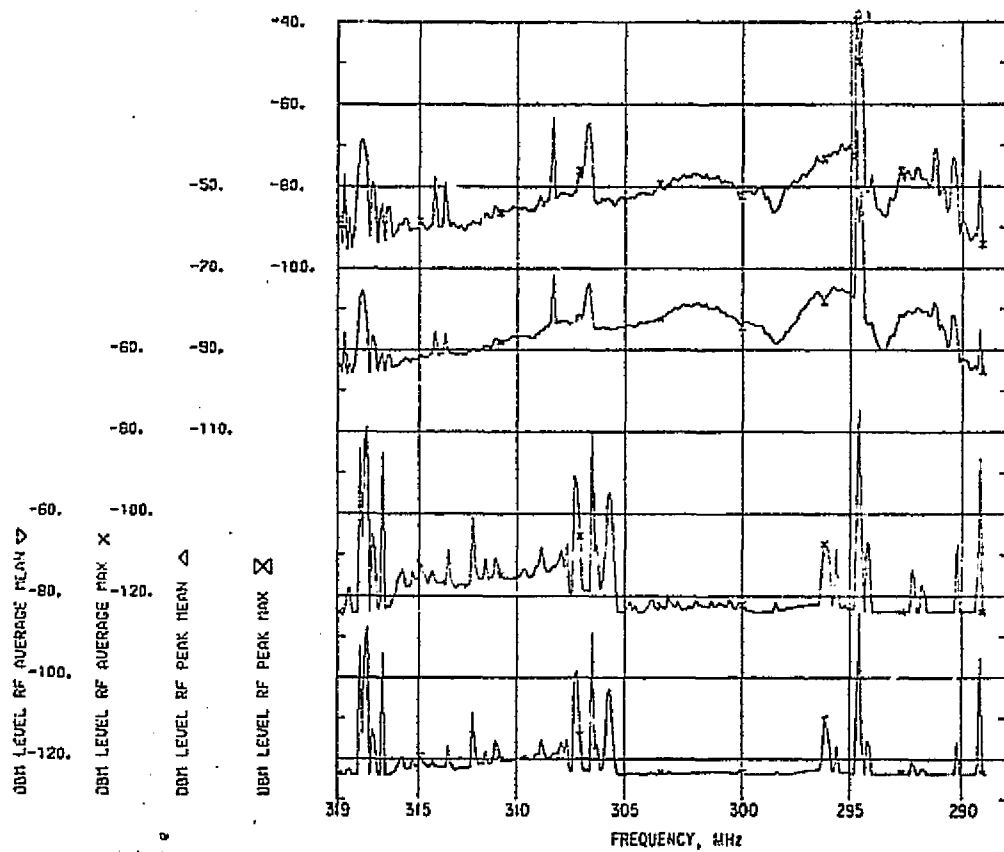
Fig. 5 Noise Level as a Function of Frequency (Eastern United States - Cape Cod to Dayton) (from Ref 27).
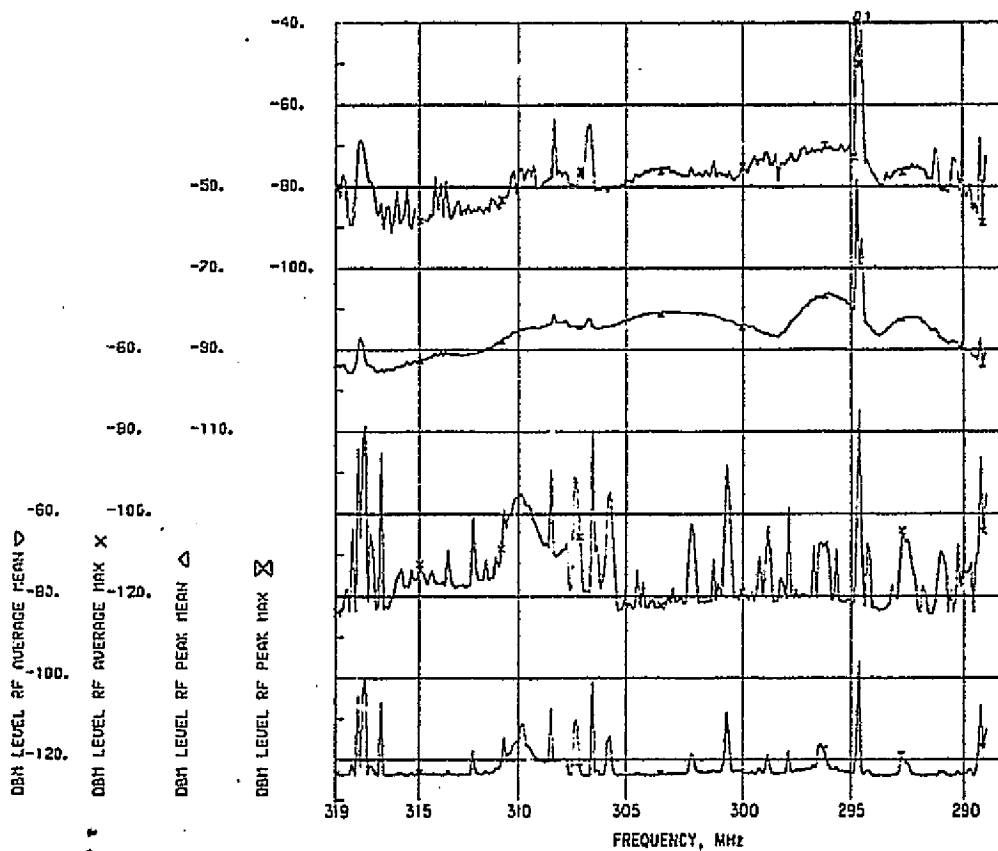
Fig. 6   Noise Level as a Function of Frequency--Mideast,
Europe, and Eastern United States (from Ref. 27).

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entire region. This survey measured peak and average power at an altitude of 30,000 ft, quantized in steps of 5 dBm in each 30 kHz channel from 100 to 500 MHz using a computer controlled spectrum analyzer mounted in a KC-135. The view of the log periodic antennas was 360 miles wide. The measurements were made viewing a wide angle looking forward from the aircraft with the center of the main lobe about 0.2° below the horizon. Various bands in this portion of the spectrum are allocated for fixed mobile operation, aeronautical radio-navigation, broadcast, and space and meteorological aids. The report includes graphs of average power levels in each channel, and graphs of channel occupancy, and the text and accompanying tables note hourly or day to day variations. Fig. 7 shows the results of measurements of average power levels from 400 to 410 MHz. The baseline of noise was at about -108 dBm for most of the surveys made in the 400-406 MHz band (ITU Meteorological). Occupancy is defined as the percent of time that the level in a 30 kHz channel is above -99 dBm. This band was occupied less than 10% of the time except on the occasion where the average level went to -115 dBm/kHz, when the occupancy rose to nearly 100 percent. This was possible due to a signal near 404.0 MHz.

The 450 to 470 band (ITF Fixed Mobile) was found to be in much more intensive use. The levels of average power in this band are shown in Figs. 8 and 9. The baseline level here ranged from about -100 dB to about -110 dBm.

The distribution of received power levels for several flights are shown on Fig. 13. The received level never rose above -80 dBm and remained below -90 dBm for more than 90% of the time. In this survey, no attempt was made by the investigators to separate coherent sources from noncoherent sources.

According to this survey, the 400-406 MHz band showed the lowest occupancy and average power levels of all the bands above 400 MHz, with average power levels typically around -110 dBm.

Occupancy and average power in the various fixed mobile bands was varied, albeit evenly distributed within each band. Average power levels extended as high as -80 dBm.

Average power levels across the 470 to 500 MHz UHF broadcast band (Figs. 10-12) were substantially higher (up to -56 dBm) but very regular: one sees virtually the same set of peaks for each TV channel. A survey looking at the continental U.S. might see a similar set of peaks repeated every 6 MHz across the entire 470-806 MHz portion of the spectrum.

One set of information from a satellite, Nimbus -4 [29] reports levels of radio interference at 401.5 MHz (down-link) and 466 MHz (up-link) (Fig. 14). Up-link interference ranges from above -110 dBm to below -130 dBm. No data is given on area of view, receiver characteristics, or how the measurements were made.
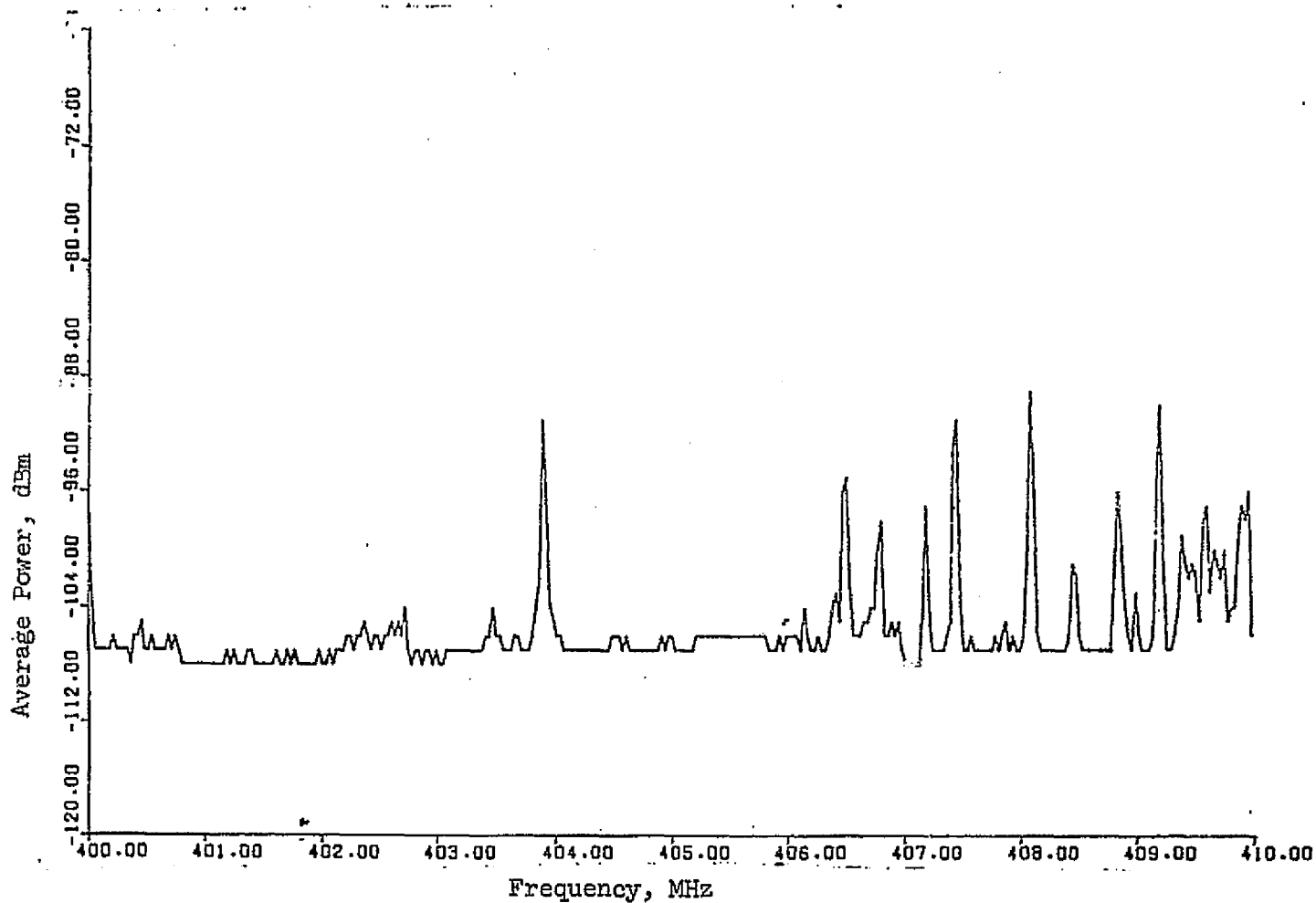
Fig. 7   Average Power Levels over Europe in the 400-410 MHz Band
as Measured at 30,000 ft with Antenna Looking Forward
(from Ref. 28).
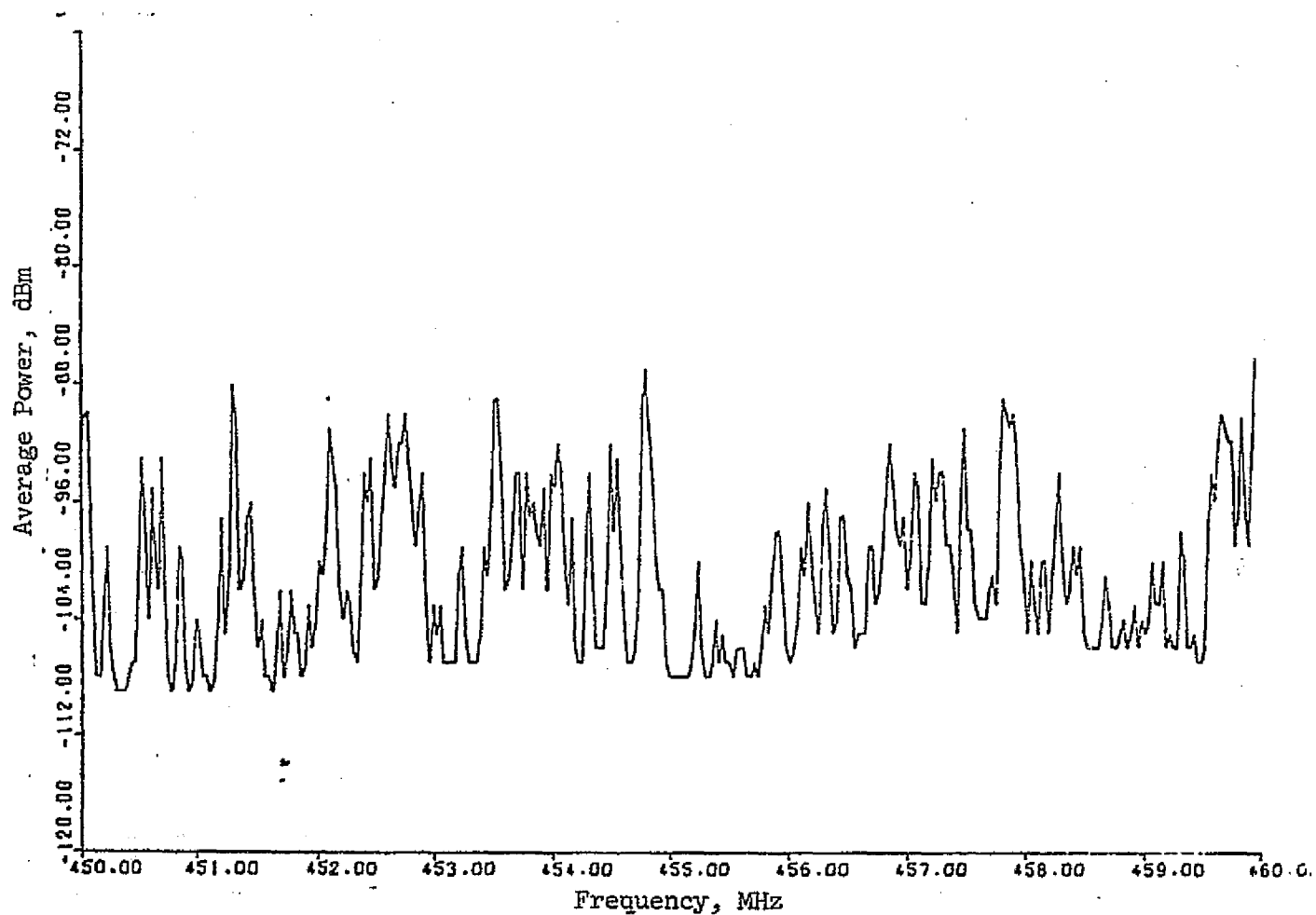
Fig. 8   Average Power Levels over Europe in the 450-460 MHz Band
as Measured at 30,000 ft with Antenna Looking Forward
(from Ref. 28).
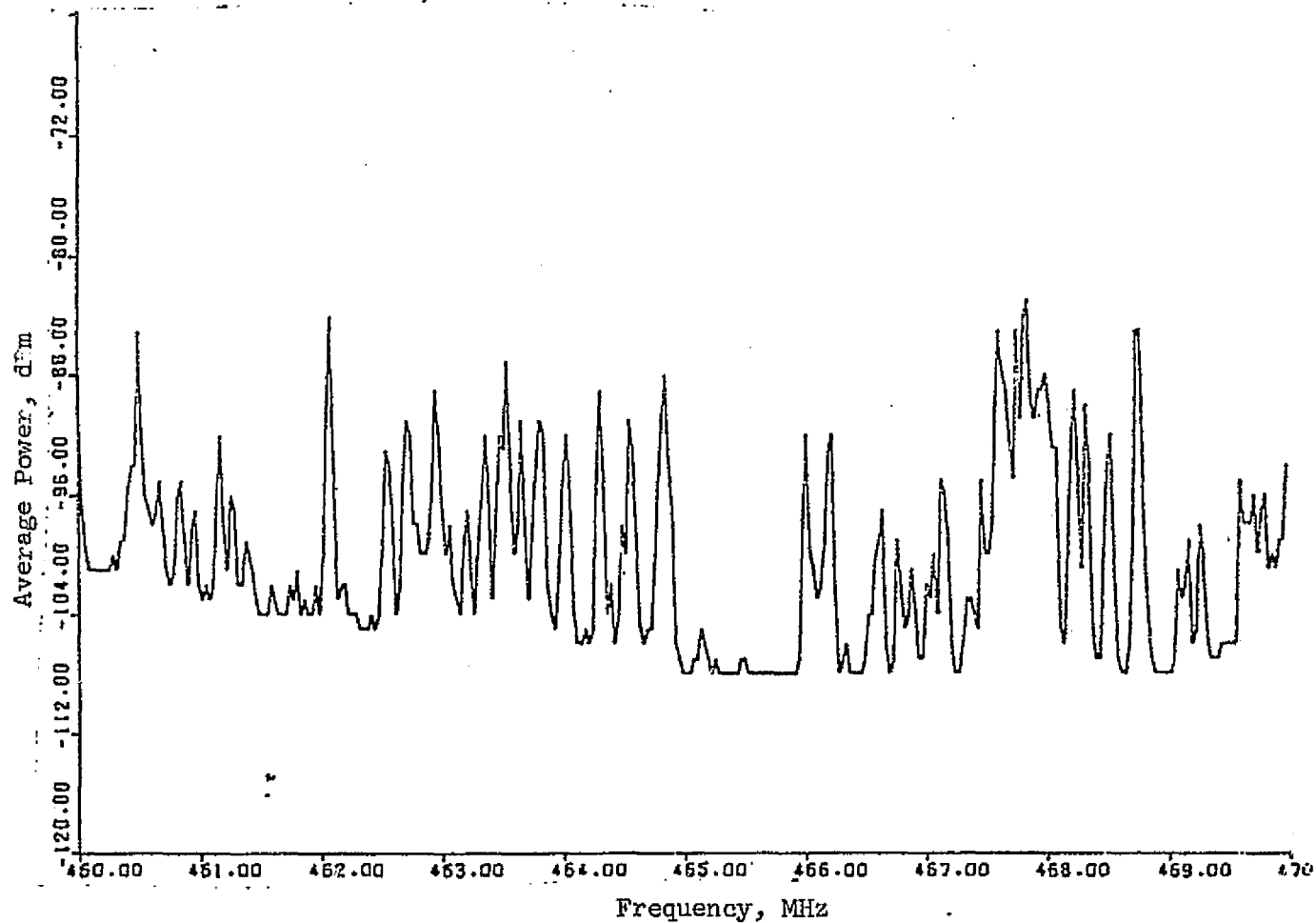
Fig. 9   Average Power Levels over Europe in the 460-470 MHz Band
          as Measured at 30,000 ft with Antenna Looking Forward
          (from Ref. 28).

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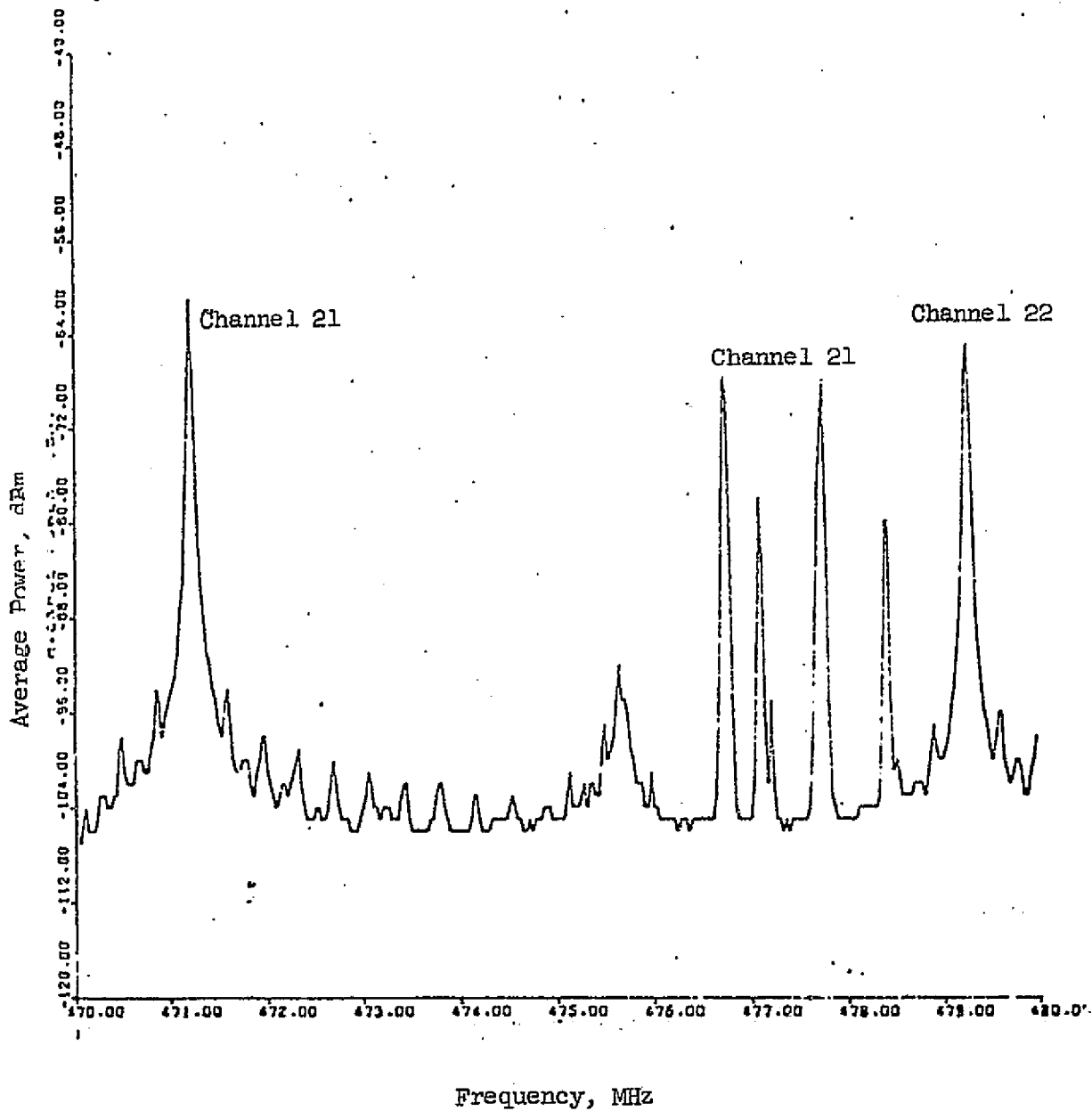
Fig. 10. Average Power Levels Over Europe in the 470-480 MHz Band as Measured at 30,000 ft. With Antenna Looking Forward (from Ref. 28)

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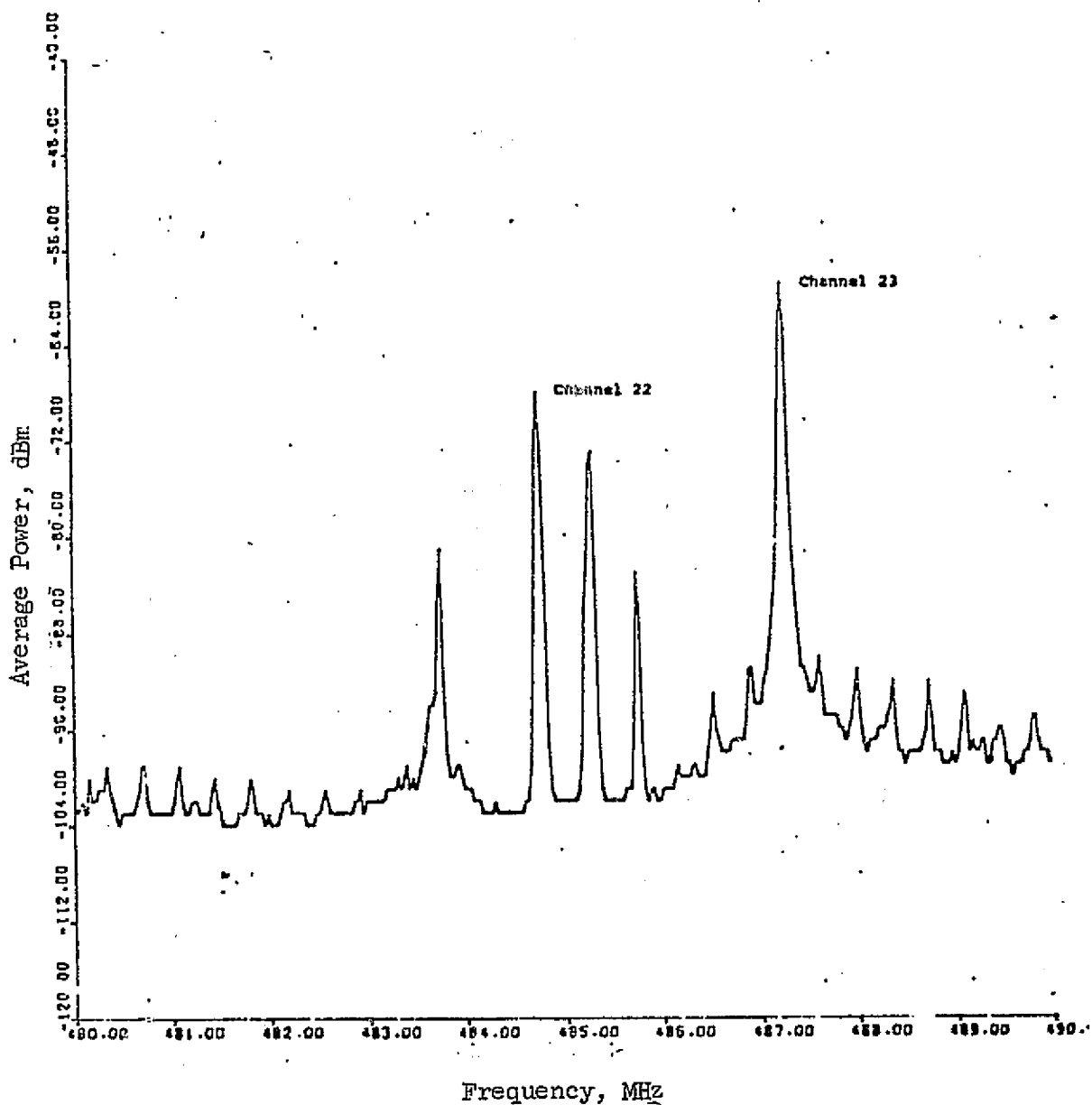
Fig. 11. Average Power Levels Over Europe in the 480-490 MHz Band as Measured at 30,000 Ft. With Antenna Looking Forward (from Ref. 28)
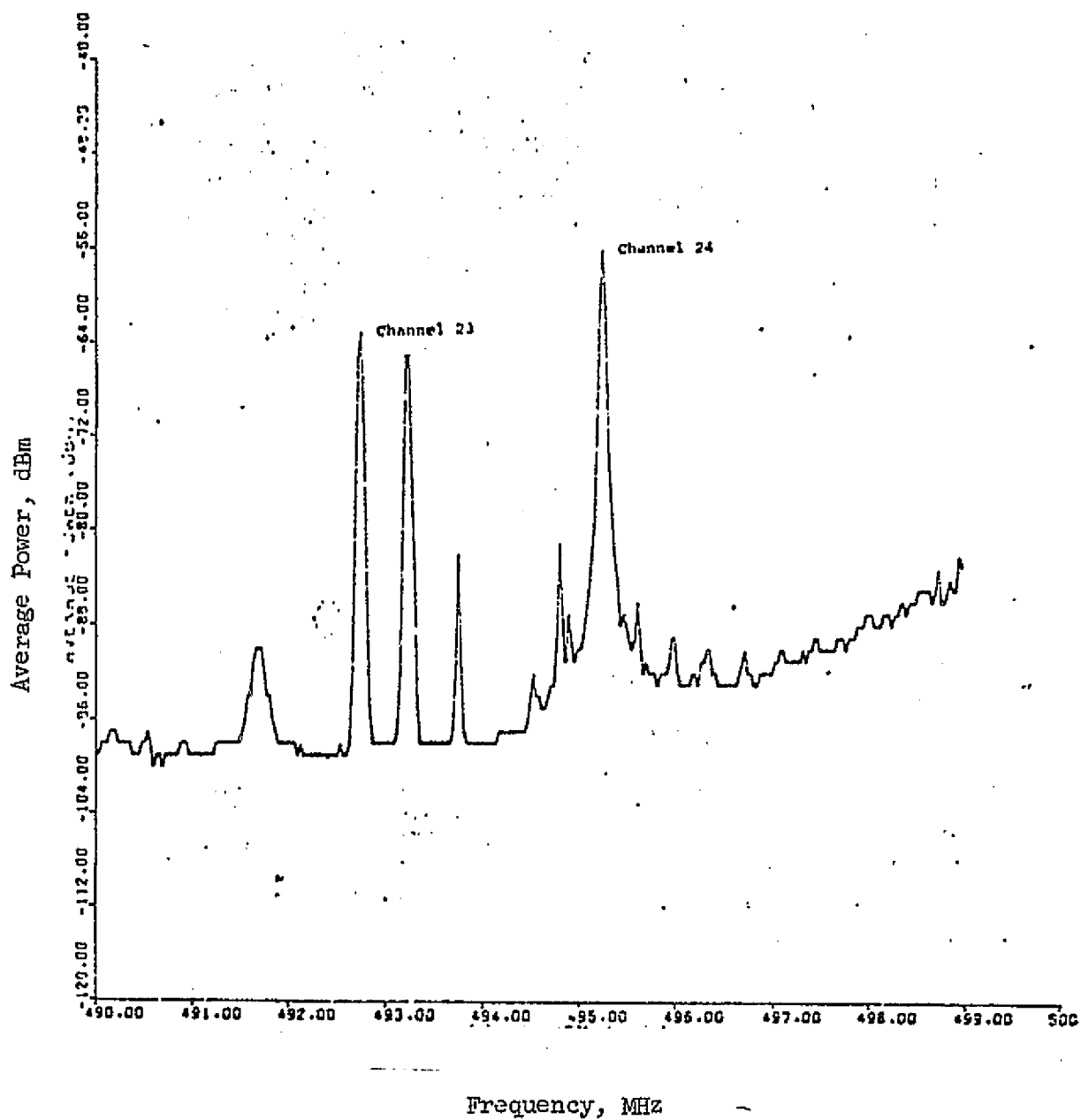
Fig. 12. Average Power Levels Over Europe in the 490-500 MHz Band as Measured at 30,000 Ft. with Antenna Looking Forward (from Ref. 28)
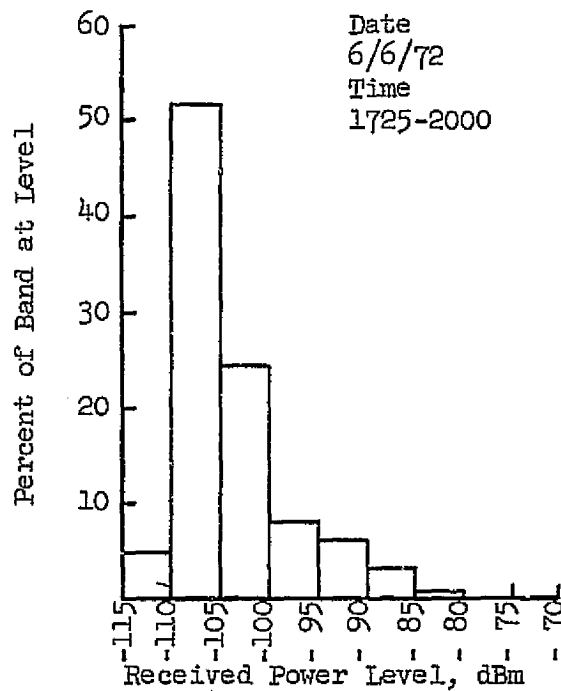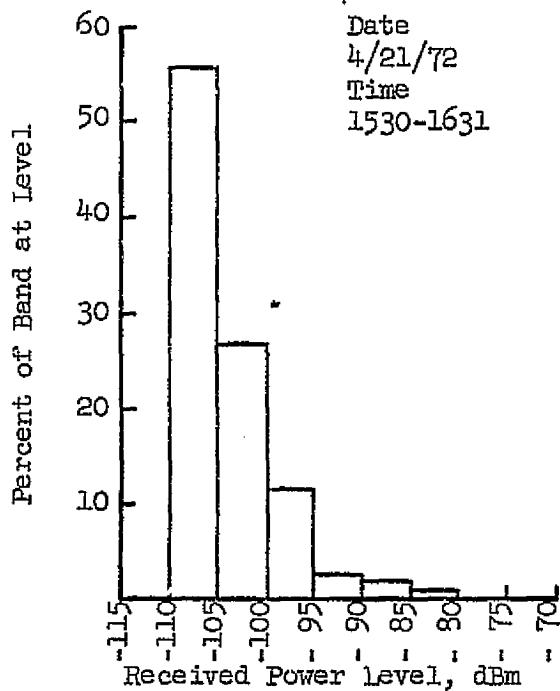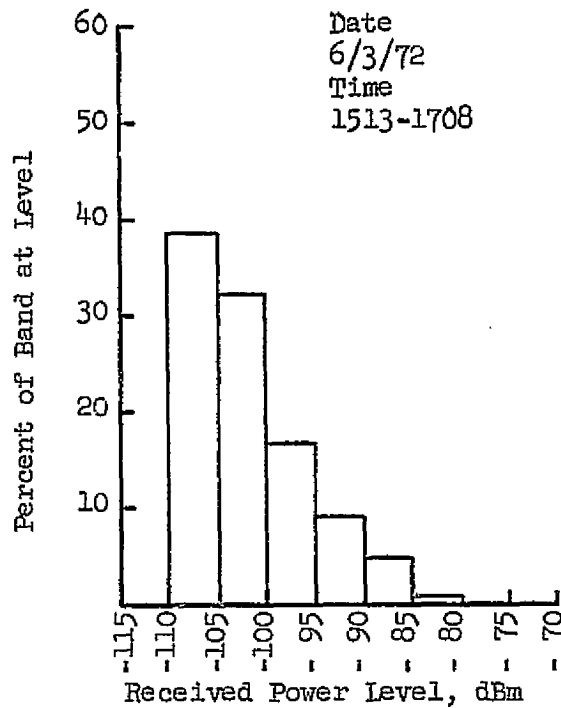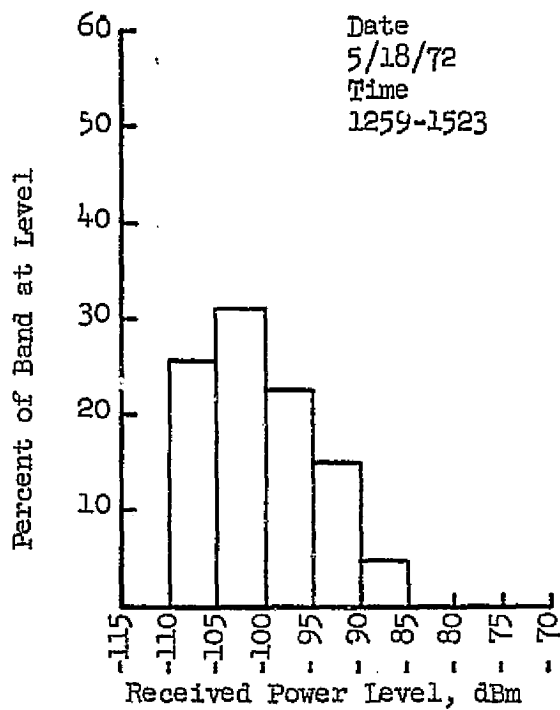
Fig. 13. Power Level Distribution of Emissions Measured over Europe at 450-470 MHz (B.W. 30 kHz) (from tabulations in Ref. 28).

	Reviewed signal ≥ -110 dBm
/////////	-110 dBm > Reviewed signal ≥ -115 dBm
	-115 dBm > Reviewed signal ≥ -120 dBm
	-120 dBm > Reviewed signal ≥ -125 dBm
\\\\\\\\	-125 dBm > Reviewed signal ≥ -130 dBm
	-130 dBm > Reviewed signal 0 (but signal still present)
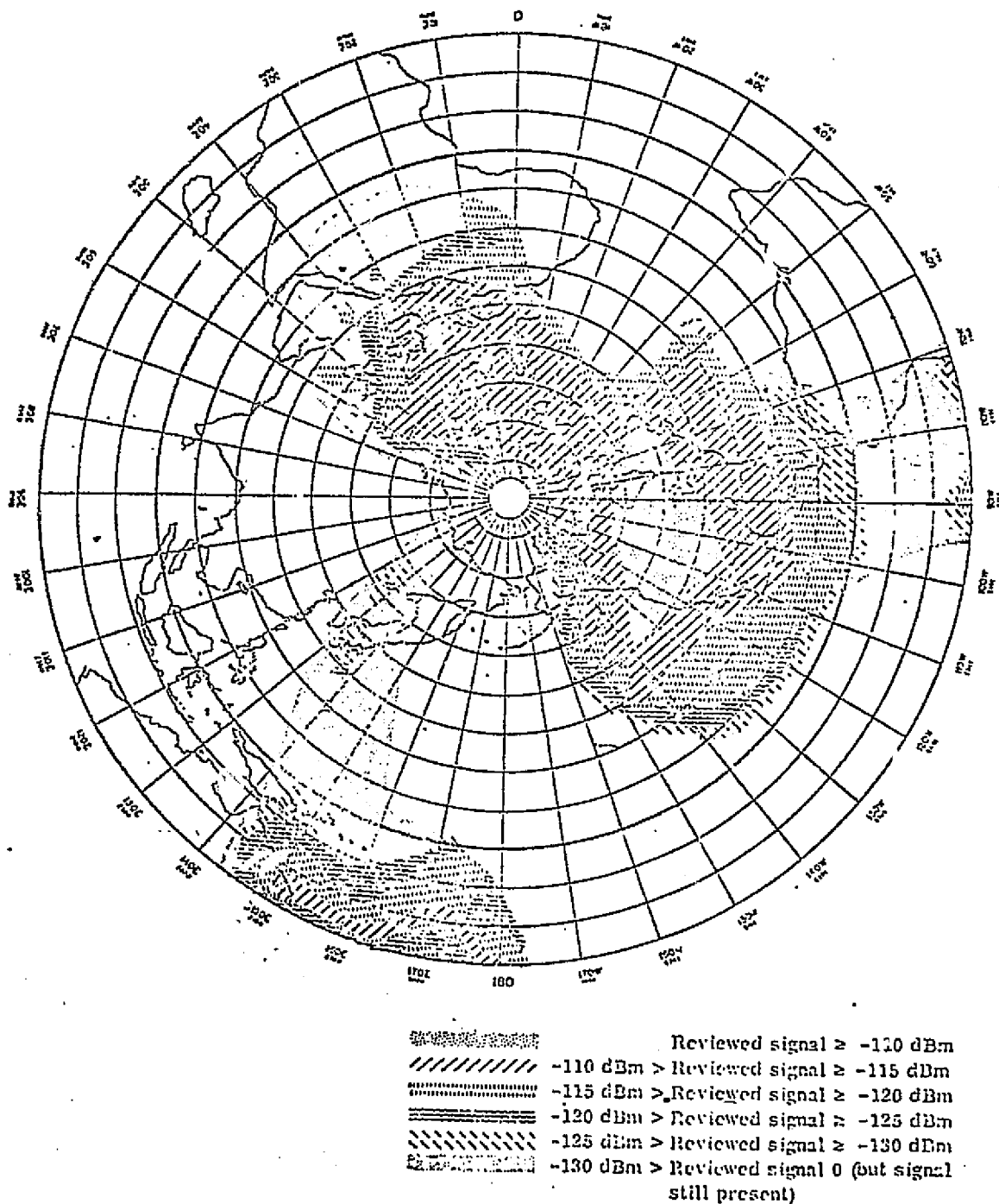
Fig. 14. Geographical Distribution of Power Levels of Interfering Signals Observed By NIMBUS-4 at 466 MHz (from Ref. 29).

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Currently the ATS-6 satellite is surveying the 6 GHz region over the continental United States from a synchronous orbit. A preliminary report of data gathered by this satellite has been received only recently, and has not as yet been fully evaluated.

The results of satellite based RFI measurements made from LES-5 and LES-6 have been reported by W.W. Ward et.al., [30,31].

LES-5, which surveyed the radio frequency environment from 253 to 283 MHz was located in a quasi-stationary subsynchronous 33,400 km orbit, drifting slowly eastward so that the entire earth, excepting the polar regions, was viewed during the nine months of the experiment. The results of these measurements are presented as frequency versus strongest signal plots and frequency versus average signal plots covering the entire period of the experiment, and for each of five geographical areas: United States, United States and Europe, Europe and Asia, United States, Asia, and Pacific, and North, Central and South America.

The weakest observable source was 100W (isotropic radiator) suggesting that all of the radiation observed was from coherent sources.

The LES-5 antenna has a gain of 2 dB, its beam being in the shape of a torus symmetrical about the axis of rotation of the satellite with a half-power beamwidth of 30° about the plane normal to it. The receiver bandwidth was 120 kHz with a sensitivity of -120 dBW and a noise figure of 3 dB at 255 MHz. The noise figure was a minimum at this frequency. Strongest signals were observed in the U.S. ranging from about -110 dBm to about -90 dBm (referenced to an isotropic antenna), most occurring in the frequency range between 254 MHz and 262 MHz where the system noise is low, and two occurring in the band between 276 MHz and 279 MHz. Similar results were recorded in the U.S. and Europe. The strongest signals observed in the Asia, Pacific, and U.S. and the North, South, and Central Americas were similarly distributed in frequency but at a level 5 to 10 dB lower.

The LES-6, which surveyed the radio frequency environment from 290 to 315 MHz, was located in synchronous, station kept orbit near 90° West longitude from November 1968 through July 1969 and repositioned eastward thereafter with data being reported until October when it had reached about 60° East longitude. The results of these measurements are presented in four plots: (1) average signal power observed between 0600 and 2200 Central Standard Time; (2) average signal power observed between 2200 and 0600 Central Standard Time; (3) peak signal power observed between 0600 and 2200 Central Standard Time; and (4) peak signal power observed between 2200 and 0600 Central Standard Time. The antenna had a gain of 10 dB and half power beamwidths of 34° (parallel with the earth's axis) and 54° (normal to the earth's axis), which allowed LES-6 to view the entire visible portion of the earth. The receiver had a bandwidth of 120 kHz, a sensitivity of -120 dBm and a noise figure of 3 dB. The weakest observable signal was 25W (isotropic radiator). Data was presented, corrected to equivalent noise power received by an isotropic antenna.

The average power plot shows a baseline level near the system noise level throughout most of the band with some salients rising from 10 to 15 dB higher. The average peak power plot shows a baseline ranging from about -100 dBm at 288 MHz to about -110 dBm at 300 MHz and above. The strongest peak power signals in the band rose to about -80 dBm with the baseline of the plot of strongest peak power being at about -105 dBm.

2.2 Intentional Emissions

In addition to emissions intentionally directed upward toward satellite or space vehicles, the coherent sources that an earth directed satellite based receiver might see looking at the 400 MHz to 40 GHz part of the spectrum include:
1. Radar
2. Other radio navigation aids
3. UHF-TV
4. Microwave line-of-sight transmitters

Of these, the radars and UHF-TV transmitters have the highest peak powers; either can range as high as 5 megawatts (MW).

2.2.1 Radar

Radars, having power outputs above 100W, are expected to be the most prominent emitters in this portion of the spectrum. White [32] notes that "as of 1972, there are about 3000 fixed radar systems in the U.S. (an average of one radar per 24 square miles of urban-suburban area), adding the restriction "excluding airborne, mobile, waterborne, and classified military CE installations". Radars in the last-mentioned category are undoubtedly quite numerous and quite powerful. White further notes that peak-pulse power for large fixed radars ranges from 100 kW to 5 MW.

The FAA Frequency Assignment Bureau has provided data on airport and airway radars which are presented in Table 4.

White also asserts that if we include all types of radars -- air traffic control, air and surface search, harbor surveillance, mapping, tracking and fire control, police speed-monitoring, and weather, there may be upwards of 100,000 emitters using various portions of the spectrum between 225 MHz and 35 GHz in the U.S. alone. Most of these are low power police speed monitors. Cridlan [33] points out that both magnetrons and klystons used in high power radars produce signals with substantial unwanted harmonics and spurious emissions both above and below the fundamental frequency. These spurious signals may fall into bands allocated to other users. Many of these spurious emissions from high power radars in the L and C bands can have EIRP's higher than 20 dBW (100W).

TABLE 4:   CIVILIAN AIRPORT RADARS

Type	Beacon	Long Range	Short Range	Detection
Frequency	1030 MHz interrogate 1090 MHz answer	1250-1350 MHz	2700-2900 MHz	23-24 GHz
Number in CONUS	800-900	85	110	9
Peak Power	1-1.5kW	5MW	600kW	50kW
PRF, pps	350-400	350-370	1200	14,400
Pulse Width	---	2μs	0.8μs	0.02μs
Antenna Rotation Rate	13-15 rpm	5rpm	---	60 rpm
Antenna Gain	38 dB	34 dB	---	---
Beamwidth (3 dB)				
Horizonal	4-5°	1.5°	1.5°	---
Vertical	30°	5-30°	5.30°	---

In the late 1950's Myers [34] measured L-band (1-1. ¹ GHz) and
S-band (2.7-3.9 GHz) radar signal densities at 20,000 feet over a number
of American cities including Los Angeles, San Francisco, New York,
Boston, and Pittsburgh. Myers presented some of these data in terms of
number of pulses above -70 dBm received per second. The maximum number
of pulses per second was about 5000 over Los Angeles but reached 80,000
over Pittsburgh. While these measurements are undoubtedly not accurate
today, he makes several observations that may still be valid: the pulse
rate above the L-band (in the 1400-2000 MHz range) was about 10% of
the pulse rate within L-band, and the levels in the 1400-2000 MHz range
were about 30-40 dB below the levels within L-band. These correlations
are consistent with Cridlan's measurements of spurious signals from
L-band radars.

2.2 2 Other Navigational Aids

The principal type of navigational aid operating above 400 MHz is
TACAN, which occupies the band 960-1215 MHz. TACAN ground stations
radiate 1 to 5 kW average power and 6 or 10 kW peak power in a rotating
nine-lobed pattern. There are 1013 of these stations in the Continental
United States and there are estimated to be 20,000 aircraft equipped
to use TACAN, each airborne equipment radiating 1.5 kW peak power.

2.2.3 UHF Television

UHF television broadcasting in the United States occupies the fre-
quency band extending from 470 MHz through 806 MHz (Channels 14-69)*. It
is divided into 56 channels, each having a 6 MHz bandwidth. Radiated
power is limited by the FCC to between 5,000 kW and 500 kW, [35] depending
on antenna height. Further information is being sought concerning the
numbers and distribution of these transmitters in the United States.
It is, however, expected that most of these stations radiate high levels
of power and that most of this power will be directed toward the horizon,
so that the levels received will be similar with those reported from the
IIT survey over Europe [28]. These levels ranged from about 60 to 70
dBm/kHz as measured using an antenna with a gain of from 8 to 10 dB.

Unused portions of this band are shared with other radio services
including:

1. 716 to 890 MHz may be used in Southern Florida for International
Fixed Public Radio Communications.

2. 800 to 830 MHz may be used in part of Alaska for fixed station
Domestic Public Radio Service.

The band 608 to 614 MHz was reserved for Radio Astronomy until January 1,
1974.

2.2.4 Line-Of-Sight Microwave Communication Systems

Microwave line-of-sight communication systems are a potential source
of observable intentional radiation. These systems include common carrier
systems, television broadcast auxiliary service, cable television
auxiliary links, and those which are part of other radio

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* Channels 70 through 83 (806-890 MHz) available only in Puerto Rico.

services such as aviation radio services, industrial radio service, land transportation radio service, and satellite communication. Narrow beams and low powers, less than 20 watts, are used in these systems.

Microwave systems using frequencies above 952 MHz, excepting common carriers, broadcast auxiliary services, and cable television auxiliary services, are regulated by the FCC in accordance with the Microwave Technical Standards Table [35] presented here in Table 5. The values shown here may be assumed to be worst case, since in granting a station license, the FCC requires that the power transmitted be the minimum needed to accomplish the purpose of the transmitter.

The quantities and pertinent characteristics of microwave trans-mitters operating in the broadcast auxiliary radio service [36], cable television auxiliary service [37] and common carrier radio service [38] in the United States are summarized in Table 6. It is noted that trans-mitter powers, where they have been identified, are well within the levels allowed other similar services occupying nearby bands as listed in Table 5. As an example, MCI Telecommunications transmitters use only 2W [39] in the 11 GHz band where the listing in the Microwave Technical Standards Table is 5W, and 5W in the 2 GHz band where 15W is indicated as being allowable in nearby bands.

The preferred bands for International Radio-Relay Systems operating at microwave frequencies are presented in Table 7 [40]. It is assumed that the power levels used at these frequencies are similar to those used in the United States.

Table 5. Microwave Technical Standards

Frequency band (MHz)	Power [1] (watts)	Tolerance (percent)	Bandwidth [2]	Beamwidth [3]
952-960	[8] 30	.0005	100 kHz	[7] 20°
1850-1990	18	.02	8 MHz	10°
2130-2150	15	.001	800 kHz	10°
2150-2160	15	.001	10 MHz	360°
2180-2200	15	.001	800 kHz	10°
2450-2500 [4]	12	(5)	(5)	(4)
2650-2656 [6]				
2662-2668 [6]				
2674-2680 [6]				
2686.9375 [9]				
2687.9375 [9]				
2688.9375 [9]				
5325-6575	7	.02	25 MHz	7°
6575-6875	7	.02	10 MHz	5°
10550-10680	5	(4)	25 MHz	4°
12200-12700	5	.05	20 MHz	4°
Above 16000	5	(5)	50 MHz	(4)

[1] Maximum rated power output of transmitter. Power in excess of that shown herein will be authorized only if specifically provided on a particular frequency or under exceptional circumstances based upon a factual showing of need. For pulsed systems average power shall be limited to the values shown, peak power shall not exceed five times this limit.

[2] Maximum bandwidth (necessary or occupied, whichever is greater) which will be authorized. Except in the 2130-2150 and 2180-2200 MHz bands, consideration will be given, on a case-by-case basis, to requests for additional adjacent channels based upon a complete and specific factual showing of unique or unusual circumstances, apart from economic considerations, requiring such additional channels. In the band 952-960 MHz bandwidths up to 500 kHz may be authorized.

[3] Maximum beamwidth of major lobe between 0.5 power points in horizontal plane. Exceptions may be granted for stations in remote areas or until harmful interference is caused to other stations operating in accordance with these provisions.

[4] Subject to no protection from ISM equipment on 2450 MHz.

[5] To be specified in the station authorization.

[6] This frequency band is available only for operational fixed stations employing television transmissions. The transmitting equipment for such stations shall meet the technical standards, prescribed for instructional television fixed stations contained in Part 74, Subpart I, § 74.901, et seq. of this chapter. Use of these frequencies in the Land Transportation Radio Services is secondary to stations in the Public Safety Radio Services. Operational fixed stations authorized in the band 2500-2690 MHz prior to July 16, 1971, may continue to be authorized on a co-equal basis to other stations operating in accordance with the Table of Frequency Allocations. No expansion of existing systems on frequencies not allocated to this service will be permitted. Additional stations or new assignments may be authorized only in accordance with the provisions of this section.

[7] Except for the frequencies 952.1, 952.2, 952.3, and 952.4 MHz and the frequency pairs 952.8 and 956.4; 952.9 and 956.5; 956.2 and 959.8; and 956.3 and 959.9 MHz, where the beamwidth may be 360°.

[8] Except for the frequencies 952.1, 952.2, 952.3, and 952.4 MHz, where the maximum power may be 100 watts.

[9] Response frequencies. When authorized they are to be paired respectively with the bands 2650-2656, 2662-2668, and 2674-2680 MHz, and used in accordance with the technical standards prescribed for ITFS response stations in Part 74, Subpart I, of this chapter.

Source: FCC Regulations, part 93.111

TABLE 6.   MICROWAVE TRANSMITTER QUANTITIES AND CHARACTERISTICS (U.S.A.)

Service	Number of Transmitters	Frequencies MHz	Power
Common Carrier	7,970 sites	2,110 - 2,130 2,160 - 2,180 3,700 - 4,200 5,925 - 6,425 10,700 - 11,700	2W - 20W Usually below 10W 5W average

Television Broadcast Auxiliary Service
 	
Includes:
  intercity
  remote pickup
  STL
	2,866	950
		
		1,990 - 2,110
		
		6,875 - 7,125
		
		12,700 - 13,200
			10W maximum
			
			1.5W - 2W typical

Cable Television	approx. 200	12,700 - 12,950	-58 to -10 dBW

TABLE 7. PREFERRED RF BANDS FOR INTERNATIONAL RADIO-RELAY SYSTEMS, CCIR RECOMMENDATIONS

Maximum capacity of each radio carrier (telephone channels or television)	Nominal limits of radio frequency band, MHz	Preferred 'center' frequency f_0, MHz	Width of RF band occupied, MHz
60-120 (Recommendation No. 283)	1,700 - 1,900 1,900 - 2,100 (2,000 MHz band) 2,100 - 2,300	1,808 2,000 2,203	200 200
60-120 (Recommendation No. 284)	7,425 - 7,725 (7,000 MHz band)	7,557-5	300
300 - 1,800 or television or equivalent (Recommendation Nos. 278, 279, and 281)	1,700 - 2,100 (2,000 MHz band) 1,900 - 2,300 3,800 - 4,200* (4,000 MHz band)	1,903 2,101 4,003.5	400 400 400
600-1,800 or television or equivalent (Recommendations Nos. 280 and 281)	5,925 - 6,425 (6,000 MHz band)	6,175	500

* In Regions 2 and 3 the band 3,700 - 4,200 MHz is used.

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3.0 DEVELOPMENT OF EXPERIMENT

3.1 EEE System Design Parameters

In this section the major system parameters relating to the design of an experiment for measuring emissions from the earth at an orbiting, near earth satellite are discussed. Its purpose is to show how these parameters are related one to another, and thus to establish the trade-offs between them. For example, large antennas at the satellite would make the equipment more sensitive to emissions from the earth but would require a more detailed examination of the surface of the earth in order to detect all possible emitters.

We begin with the basic relationship between radiated and received powers and antenna effective areas. From Friis' propagation equation

$$P_r = P_t \frac{A_r A_t}{\lambda^2 d^2} \tag{1}$$

P_r = power received, watts

P_t = power transmitted, watts

A_r = receiver antenna effective area, m^2

A_t = transmitter antenna effective area, m^2

λ = wavelength of radiation, m

d = distance between receiving and transmitting antennas, m

The effective area of the antenna can be related to its effective gain relative to an isotropic radiator in any direction θ, Φ by means of

$$A \; eff(\theta,\Phi) = \frac{\lambda^2 G(\theta,\Phi)}{4\pi} \tag{2}$$

Assume that in the case of the receiving antenna one is interested in the maximum gain and that the pattern of the antenna can be defined in terms of a main lobe which has a circular cross-section subtending a total angle α in radians (over which the gain is assumed to be constant). The gain can be approximated, for small angles, by the expression $16/\alpha^2$. Substituting this result along with (2) into (1), gives

$$P_r = \frac{P_t G_t \lambda^2}{\pi^2 \ell^2} \tag{3}$$

in which the substitution

$$\ell = d\alpha \tag{4}$$

has been made, where:

ℓ = length subtended by the receiver antenna beam along the surface when the beam is directed normally to the earth.

Now, if the minimum detectable signal power at the receiver is defined as that power which is equal to the equivalent noise input power kT_eB where B is the bandwidth, k the Boltzmann's constant, and T_e the effective system temperature, the minimum detectable effective isotropic radiated power $(EIRP)_{min}$ $(=P_tG_t)$ is

$$(EIRP)_{min} = \frac{\pi^2 kT_e B}{\lambda^2} \ell^2, \text{ watts} \tag{5}$$

In concept, the satellite is to scan simultaneously both spatially and in frequency. The maximum rate at which one can scan in frequency past a particular emitter without substantial loss in receiver response is given by [Ref. 41, p. 65]

$$F = \frac{B^2 T}{\eta}, \text{ Hz} \tag{6}$$

in which

F = frequency range scanned, Hz

B = bandwidth of the scanning aperture, Hz

T = dwell time on a particular geographical area, s

η = a factor which can be of the order of unity for detection of sinusoids or larger for detection of random type signals.*

For gross calculation purposes a geographic scanning discipline is assumed in which the dwell time on any particular point (emitter) on the surface of the earth is nearly the same as for any other point. This condition is closely achieved in optical scanning techniques using a rotating prism in which a strip of surface of length y is completely scanned in the time it takes the vehicle to advance one strip width. The length y is assumed to be small compared with the prism (vehicle) height and the element of the strip seen at any instant is rectangular in cross section. With a radio frequency antenna the element is not rectangular, nor are the boundaries of the element sharply defined, hence not all points on the surface will be exposed for the same dwell time, and some points may be scanned more than once. Furthermore, the antenna will probably be required to scan left to right and then return right to left causing further loss in scanning efficiency.

In spite of these complications the minimum time (T_t) required to scan an area A can be estimated by multiplying the dwell time T by the area A and dividing by the area subtended by the cross section on the earth's surface $(\pi\ell^2/4)$

$$T_t = \frac{4AT}{\pi\ell^2} \tag{7}$$

* See discussion on dwell time in section 3.3.1(d).

Substituting (5) and (6) in (7), with $\eta = 1$ (for detection of sine wave type signals), one obtains (8) which gives the total time to scan a geographical area A over frequency range F:

$$T_t = \frac{4\pi}{\lambda^2 B^2} \frac{kT_e B \, FA}{(EIRP)_{min}} , \text{ sec} \qquad (8)$$

To relate this result to the motion of the vehicle, one can express the area scanned in one second in terms of the linear velocity of the spacecraft (v) by the following relation:

$$A = yv \qquad (9)$$

where y = the length of the surface path scanned measured in the direction normal to the flight path. Then, taking the total scan time T_t = 1 second, (8) becomes

$$Fy = \frac{\lambda^2 B^2}{4\pi v} \frac{(EIRP)_{min}}{kT_e B} , \text{ m Hz} \qquad (10)$$

This relation can be simplified by rewriting (5):

$$\ell = \frac{\lambda}{\pi} \sqrt{\frac{(EIRP)_{min}}{kT_e B}} \qquad (11)$$

and for (10)

$$Fy = \frac{\pi}{4v} \ell^2 B^2 \qquad (12)$$

Note that both of these relations are not explicitly dependent upon the altitude, but to have the same value of ℓ at different altitudes would require antennas with different gains. Equation (11) is plotted on Fig. 15 with frequency as a parameter. It shows the (maximum) value of ℓ for a specified $(EIRP)_{min}$ to $kT_e B$ ratio. Equation (12) is plotted on Fig. 16 for a velocity of 4.75 mi/sec with frequency range scanned as a parameter.

As an example, assume measurements are being made in a frequency band near 1 GHz (λ = 0.3m) with a spectrum analyzer with a bandwidth B of 10 kHz, and with a desired detectable $(EIRP)_{min}$ of 100 μW. If the receiver has a sensitivity $(kT_e B)$ of 10^{-14}W, from Fig. 15, $\ell \cong 10^4$m $\approx$ 6 miles, and for a frequency scan width F of 1 GHz, the geographic scan width is (from Fig. 16):

$$y = 10^5 \text{m}$$

or about 60 miles.

For wider bandwidths or higher levels of $(EIRP)_{min}$, wider geographic and frequency scan widths are possible.

Equations (11) and (12) apply strictly only for small percentage frequency scan widths and for antenna scanning angles for which the slant range is not much different from the vehicle height. Where these conditions are not met, Eqs. (11) and (12) must be considered approximations which can be used for general system design purposes. With appropriate numerical
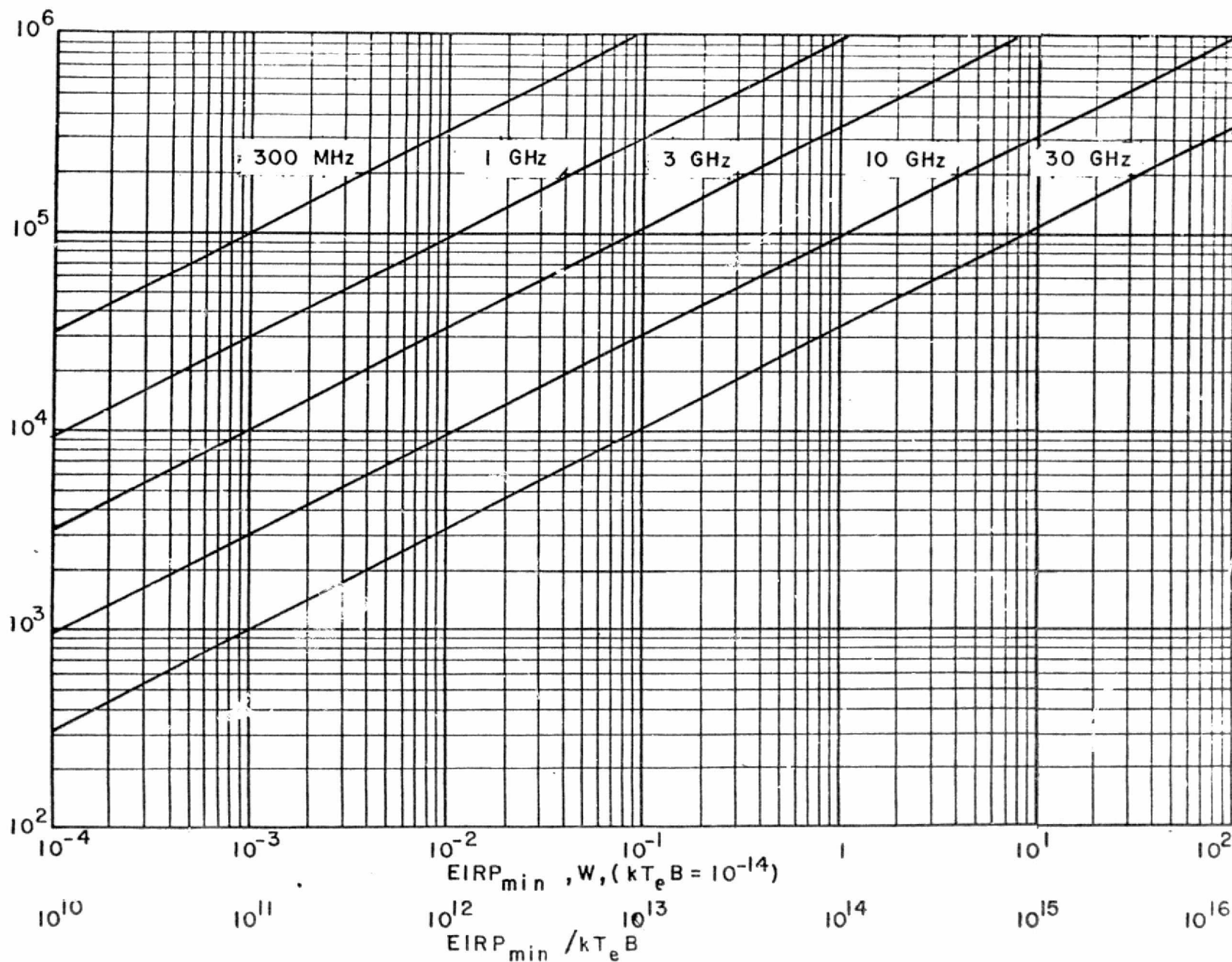
Fig. 15   Spatial Resolution (ℓ) versus Ratio $\dfrac{ETRP_{min}}{kT_e B}$

corrections they can be used for large scan widths. Further, it should be noted that for signals other than CW, such as for radar type signals, a longer dwell time may be required for detection or for signal analysis (η, Eq. 6, greater than unity) and the effective value of Fy would be reduced. The radar case is discussed on page 48.

In addition to the above, a practical question is the size of an antenna necessary to achieve a given value of geometric resolution. This is shown on Fig. 17. It is of course a function of the height of the antenna over the surface which it is viewing, as shown.

Slant Range Viewing

All the relationships derived above are based upon the concept of an antenna looking at the nadir point directly under the carrier (satellite or aircraft). The scanning disciplines discussed in section 3.2 include alternative procedures in which the antenna points at some angle with the vertical, for example an angle in which the horizon would be included in the antenna aperture. In this position, the distance from the antenna to various points on the surface of the earth within its aperture vary over quite a large range and the geometrical resolution is not a well defined quantity. The minimum value of EIRP which can be detected will vary from point to point. The formulas can be used, however, to approximate the characteristics of the configuration by assuming some nominal value of distance such as that which obtains in the direction of the center of the antenna focus. For example, for an antenna pointed close to the direction of the horizon, one might have an effective value of distance r = 1000 miles rather than, say, the nominal 250 mile distance for vertical pointing to nadir. Clearly, for the same geometrical resolution, a larger antenna would have to be used, but note that the EIRP minimum would be the same for the same value of geometrical resolution. Likewise, the effective value of transverse scan, y, would be increased somewhat. For rough approximations, however, the relationships previously derived can all be applied in this case.

3.2 Discussion of Scanning Disciplines

Earlier proposals for electromagnetic environment measurements have recommended both broad beam antennas for wide coverage or narrow beam antennas with wide sweeping angles. A shortcoming of a broad beam antenna is that it sees ground sources from a variety of angles making it difficult to isolate and to geographically pinpoint specific sources, and its sensitivity is less than that of a narrow beam antenna. On the other hand, it looks at a given area for a longer period of time than does the narrow beam antenna (unless the latter is used in a tracking mode on specific sources) and thus is more likely to intercept a source which is not emitting continuously, or one which has a rotating directional beam.

The interception probability is a complicated function of the exact geometrical relationship between the location of the transmitters with respect to the flight path, the transmitter radiated power and antenna pattern, the receiver sensitivity and its antenna pattern, and the scanning discipline in both frequency and geometry. For certain
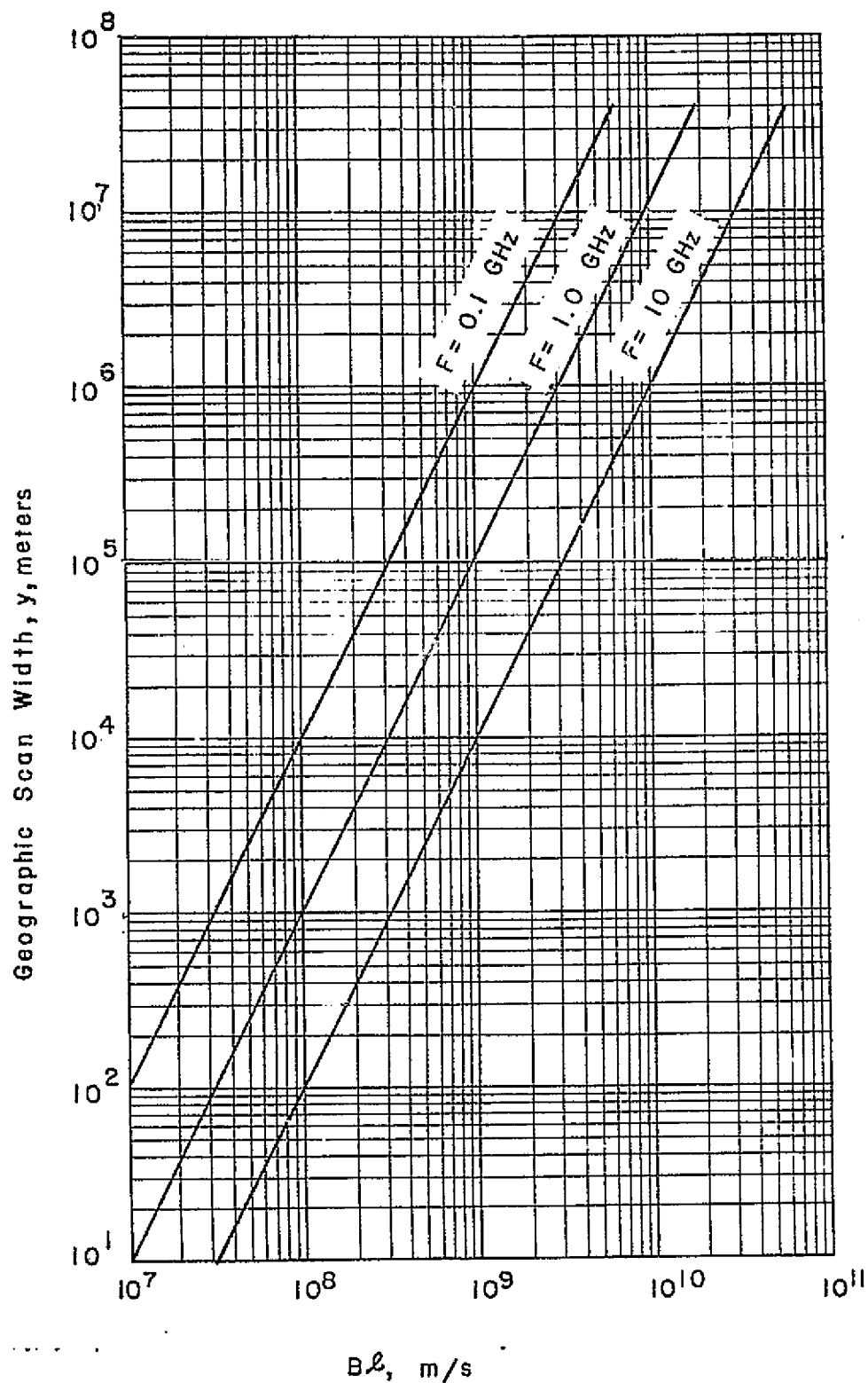
Fig. 16   Geographical Scan Width versus Product of Frequency and Spatial
Resolution (Bℓ) with the Frequency Scan Width as a Parameter.
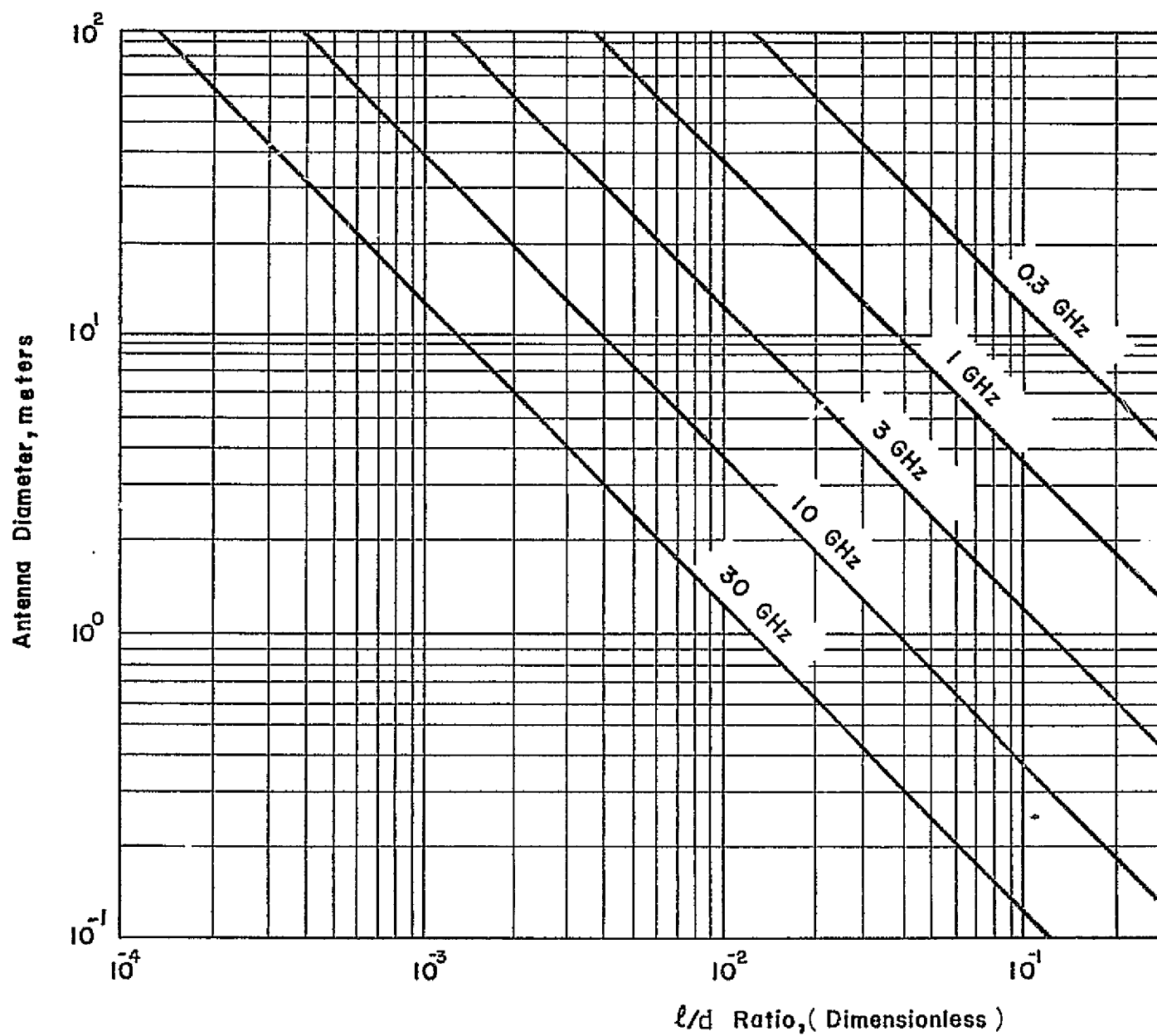v = 4.75 mi/s. Scan width y small compared to vehicle altitude.

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Fig. 17 ℓ/d versus Antenna Diameter for Various Frequencies. $\ell \cong$ beam angle.

conditions useful approximations can be given; for example, if two antennas are located at two points in a plane, the probability that their beams, if positioned at random, will intersect is:

$$\frac{\theta_1 \theta_2}{4\pi^2}$$

where θ_1 and θ_2 are the angular widths (in radians) of the two respective beams. However, note that if one of the beams rotates with a period equal or less than the dwell time of the other antenna in any specific direction, the probability of intersection can be close to unity.

In examining the ground for distributed (nonintentional) emissions, the wide beam method produces an average of the region examined, possibly washing out the effects of hot spots such as those found in urban areas. A satellite at an altitude of 250 miles has in sight a spherical cap with a radius of about 1400 miles. Such an area may include both rural and urban areas, as well as the sea. The effective average brightness temperature of the entire cap is not expected to be much higher than the nominal temperature of 300 K while the hot urban areas have been seen to be at temperatures around 30,000 K at VHF.

Using directive antennas pointing toward the horizon has a potential advantage over the vertical pointing arrangement: Since most antennas on the surface of the earth in the frequency range of interest are directive and usually aimed along the surface of the earth, a receiving antenna pointing towards the horizon would be more likely to intercept the main beam of such antennas. But since the distance from the satellite to the horizon is much greater than the distance from the satellite to the nadir, the minimum value of EIRP is also larger with this arrangement. On the other hand, it appears that the satellite receiver will have adequate sensitivity to detect most emitters of consequence. For detecting horizontally directed emissions with an antenna looking vertically, it would be necessary for the satellite to detect a side lobe of the source antenna.

It is clear that the scanning discipline used must depend in large measure on just what one wants to determine. For example, if one is concerned with interference to a specific satellite, one should use an antenna similar to that on the satellite and scan in frequency and geographical regions which are capable of producing interference. In other cases, more general frequency and geographic scans are required.

Without examining specific applications in detail, one can make the following statements:

(a) Intentional or isolated and strong unintentional sources should be measured in such a way that the number seen at one time is small, preferably just one. Frequency assignment policy, having as its purpose

the spatial isolation of sources operating at the same or adjacent frequencies, makes it unnecessary to demand high ground resolution for intentional radiators.

(b) Multiple incidental sources may be measured over an area large enough so that many contribute (to give a nearly gaussian receiver input), but not large compared to the area of the cities over which the tests are being made. The latter requirement will make it possible to see the fine structure in variations of noise brightness temperature.

(c) Sweeping methods preferably should be such that sources are examined over a limited range of angles relative to the vertical. This will result in a nearly constant footprint size, nearly constant free space loss to all sources being observed, and a restricted aspect from which the transmitter antenna pattern is being viewed.

(d) Scanning techniques should account for the effects of directional and rotational properties of both source and receiving antennas in reducing the probability of detecting individual sources.

3.3 Proposed Scanning Arrangements

(a) For measurement of incidental emission a ground footprint of between 5 and 15 miles wide will provide the fine structure of brightness temperature. This would require 1-3° of beamwidth when viewing vertically. Though intentional radiators do not require such a resolution for electrical separation, it is reasonable to expect the same antenna to be used for both incidental and intentional radiators. The high resolution will make it possible to locate reasonably accurately sources on the ground.

(b) Below 1 GHz, where a large antenna will be required to get narrow beamwidth, tests are to be made with the antenna aimed and fixed in angle. Most of the incidental contributors will be found below 1 GHz and they would generally be measured looking vertically to earth. In order to study emission patterns from selected sources, particularly the noncoherent sources, it may be possible to build in a tracking capability, automatic or manual, which will allow the antenna to alter its pointing angle, keeping a source region in constant view as the satellite passes over the source. It is conceivable that this could be done manually by the astronaut. The time spent above the horizon plane is about 10.5 minutes and the astronaut would have to follow the source in this time interval. The tracking rate, when he is looking at the horizon, would be fairly slow and would quicken as the spacecraft moves over the source. The angular tracking rate when passing immediately over a source is about 1 degree per second, maximum, for a height of 250 miles.

(c) For measurements in the microwave range (i.e., above 1 GHz) tests following the discipline described in (a) above are also recommended. Consideration is being given to the advisability of using a small angle lateral scan using either mechanical nodding or electronically switched

multiple feeds to increase the swath width. Scanning the beam 15° to each side will result in a swath of $\pm$ 60 miles on the ground without incurring excessive variation in footprint size or distance to the sources.

(d) To detect horizontally directed emission in the microwave range it is proposed that tests be run with the antenna looking to the horizon. The antenna could scan from side to side, but this would restrict its ability to detect sources directed away from it. For this reason it is proposed that it rotate in a complete circle so that a complete annulus in the horizon region is scanned. The circular rotation will insure that emissions in any direction will, sooner or later, be measured. The circular motion is simple enough and the speeds required will be shown to be slow enough to make mechanical sweep adequate. To insure detection of sources with a directional pattern having a substantial vertical component, the elevation angle of the antenna should be adjustable.

3.3.1 Development of Circular Horizon Antenna Scan Mode

The proposed circular scanning discipline is now discussed in some detail. For discussion purposes consider use of a parabolic dish of about 10 foot diameter which will have a beamwidth of about $3.2°$ at 2 GHz. At frequencies above 2 GHz the beamwidths suggested earlier can be achieved without difficulty. If this beamwidth is to be maintained at 1 GHz, a 20 foot antenna would be needed. It is to be noted that the satellite as an antenna platform is apt to have an angular fluctuation of about $1/2°$*. This suggests that a very narrow beamwidth is not in order.

a) Configuration

The configuration is shown in Fig. 18. The spacecraft antenna is assumed to be looking at an annular segment of depth, x, at the horizon, as shown. The tangent distance, t, to the horizon is found from

$$t^2 + r^2 = (r + h)^2 \qquad (13)$$

so that

$$t = h \left(1 + \frac{2r}{h} \right)^{1/2} \qquad (14)$$

where   h = height of spacecraft ($\doteq$ 250 miles)

   r = radius of earth ($\doteq$ 4000 miles)

For the approximate figures given for r and h, t is 1436 miles. The angle θ is given by

$$\theta = \sin^{-1} \frac{t}{r+h} = \sin^{-1} \frac{h}{r+h} \left(1 + \frac{2r}{h} \right)^{1/2} \qquad (15)$$
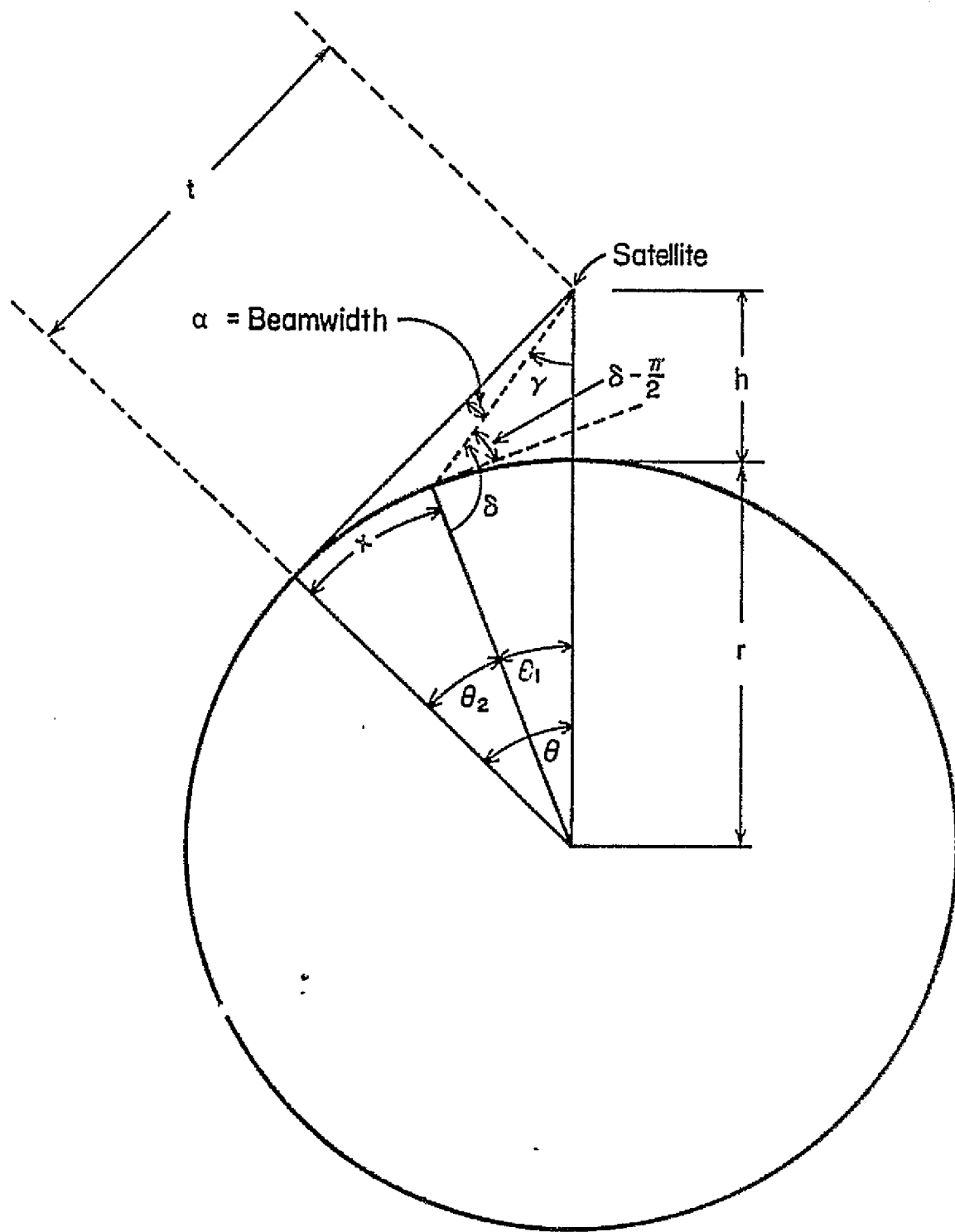
Fig. 18. Geometric Configuration, Horizon Scanning

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For the numerical values assumed here

$$\theta = 19.75^{\circ}$$

From Fig. 18

$$\delta + \gamma + \theta_1 = \pi \quad \text{and} \quad \alpha + \gamma + \theta_1 + \theta_2 = \frac{\pi}{2}$$

Hence $\qquad x = r\theta_2 = r[\delta - \pi/2 - \alpha] \qquad\qquad (16)$

Now using the law of sines

$$\sin \delta = \frac{r+h}{r} \sin \gamma$$

and $\quad \delta - \dfrac{\pi}{2} = \cos^{-1}(\sin \delta) = \cos^{-1}\left[\dfrac{r+h}{r} \cos(\theta + \alpha)\right] \qquad (17)$

For the value of h already assumed, any given value of α determines $\delta - \pi/2$ in (17) which in turn determines x in (16), as shown in Table 8.

Table 8

Depth of View at Horizon and Maximum Elevation of Ground Antenna vs Satellite Antenna Beamwidth, α, h = 250 Miles

α°	$\delta - 90^{\circ}$	x(mi)
0.5	4.56	284
1	6.50	384
2	9.30	510
4	13.46	661

Now if instead of requiring the upper limit of the beam of the satellite antenna to point to the horizon, a beam of fixed width is inclined from the nadir by an angle γ' (to the inner edge of beam), it can be shown that the arc distance subtended on the earth's surface (x') varies as follows for 1° beamwidth:

γ'(degrees)	69.25	68.25	65	50	20	0
x'(miles)	384	126	53	13	5.0	4.3

b) <u>Geographical Scanning</u>

The area viewed on the ground is suggested by the shaded area shown on Fig. 19. It shows the circular annulus being traced out over a flat surface with the satellite moving in one direction with constant speed. The band viewed by a 1° beamwidth antenna has an annular width of 384 miles. For continuous ground coverage the rate of rotation can be fixed so that the distance advanced in one rotation of the antenna (= distance from A to B on Fig. 19) will be no more than this distance. The distance A to B is

$$d_{AB} = \frac{v}{S} \text{ miles} \tag{18}$$

where v = spacecraft velocity in miles per second

   S = antenna rotation rate in rps

If d_{AB} equals x, then successive bands in the spiral are contiguous. Sources along the arc, x, assuming they transmit with main lobe axis tangent to the earth, will be seen by the spacecraft at various angles of the transmitter main lobe. The angle $(\delta - \pi/2)$ measures the maximum value of the off-axis angle. If this angle is allowed to be large, some high gain antennas would not be visible to the spacecraft passing under the spacecraft beam.

From Table 8, it can be seen that antennas with a 10° $(0 \pm 5^\circ)$ beamwidth$(\delta-90^\circ=5^\circ)$ on the ground might not be seen for an α of 1° unless successive traces of the annulus overlap. Microwave relay systems work with antenna beamwidths of 1 to 3 degrees. To see every transmitter in this category would require d_{AB} to be no more than 35 miles corresponding to $\delta = 90.5^\circ$. If d_{AB} = 340 miles, the minimum value of $\delta - \pi/2 = 5^\circ$ and

$$S = \frac{4.75}{340} = 0.014 \text{ rps} \ (= 0.84 \text{ rpm})$$

Using these parameters does not preclude the possibility of detecting narrow beam emissions. It may be that the combination of off axis emission levels and satellite receiver sensitivity will be adequate for detection.

If the earth were flat and the beam were square, the spacecraft antenna would see a quasi-rectangular area as indicated by the heavily shaded region of Fig. 19. (The actual region viewed is developed in Ref. 6 for a circular beam cross section over a spherical earth.) Its dimensions are

$$d_1 = t\,\alpha \ (= 25.07 \text{ miles if } t = 1436 \text{ miles and } \alpha = 1^\circ) \tag{19}$$

$$d_2 = (t-x)\alpha \ (= 19.8 \text{ miles if } t = 1436 \text{ miles, } x = 300 \tag{20}$$
$$\text{miles, and } \alpha = 1^\circ)$$

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Location of
satellite when
point A is in view

d_1 A

B
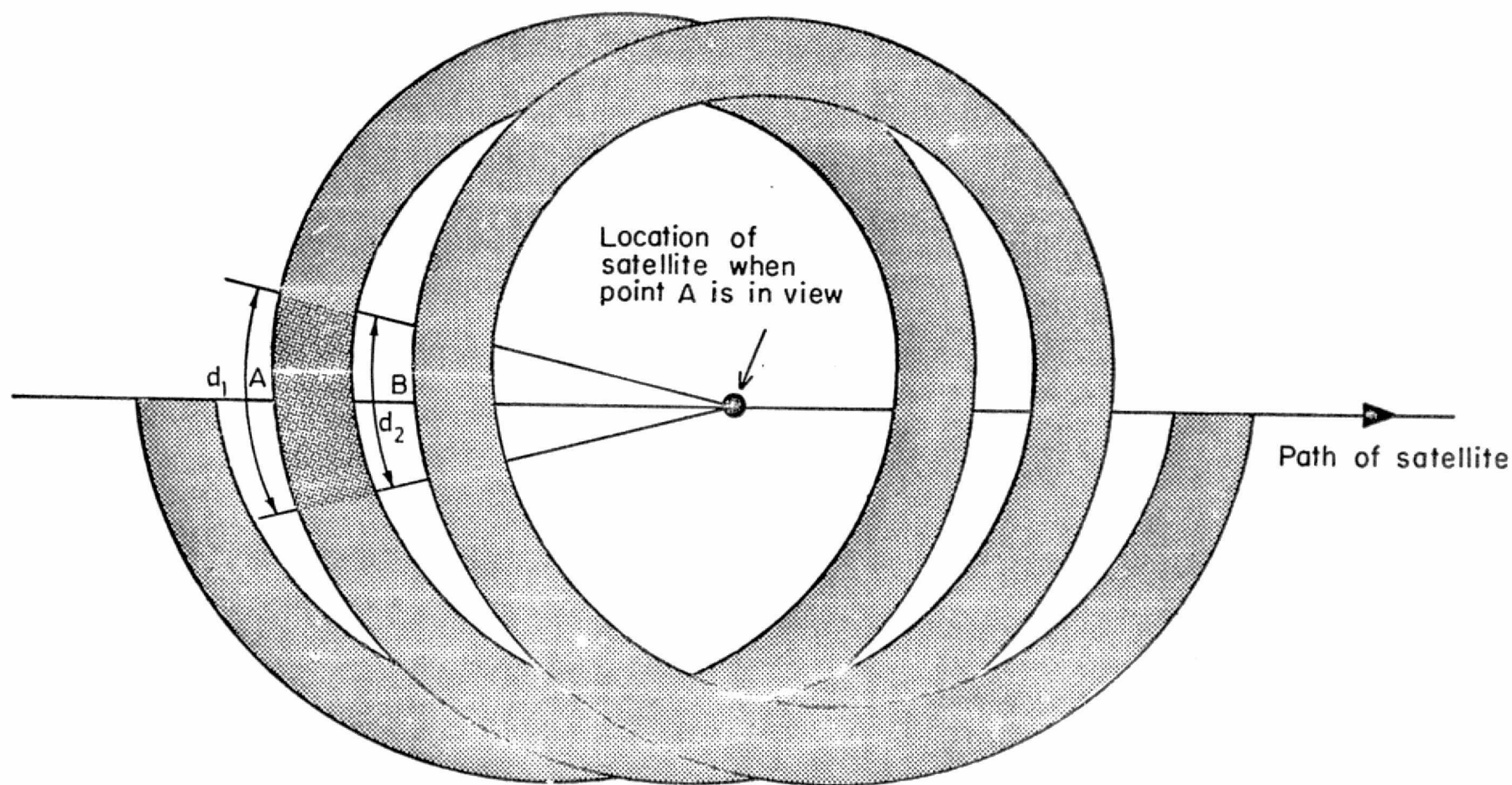
d_2

Path of satellite

Fig. 19. Surface Area Scanning Pattern

The tangential velocity of the beam at its outer extremity (omitting satellite motion) is

$$v_t = 2\pi t S (\cos \theta)$$

$$(= 118 \cdot mi/s \quad \text{for } t = 1436 \text{ miles and } S - 0.014 \text{ rps}) \quad (21)$$

A point in the heavily shaded region in Fig. 19 is in view for

$$T = \frac{\alpha}{2\pi S \cos\theta} \; s(= 0.21 \text{ seconds for } \alpha = 1^\circ, \; S = 0.014 \text{ rps}) \quad (22)$$

This is the dwell time over a source in this region and it has been expressed in terms of the spacecraft beamwidth, α, the depth of the annular region viewed, x $(= d_{AB})$, and the spacecraft velocity, v.

As mentioned in paragraph 3.2, there is no guarantee that the transmitter antenna will be oriented toward the satellite antenna when the latter has it in view. However, sources will generally be viewed a number of times from various angles increasing the probability of encountering the main beam. From Fig. 19 it can be noted that sources at the extreme left and right of the satellite track may be seen several times on a single orbit. Sources on the satellite ground track are seen twice on a single orbit. On the succeeding orbit, which is separated from it by about 1500 miles, as measured on the equator, sources encountered on the previous orbit may be seen at different angles. For fixed transmitter antennas, the main beam will sooner or later be encountered if the orbital tracks are not spatially periodic. Further work to provide quantitative relationships is planned.

c) Refraction and Doppler Effects

The foregoing assumes that rays travel in straight lines without refraction. When observing sources at the horizon, the ray is expected to undergo, in part, the refractive effect which is accounted for in microwave line-of-sight transmission by increasing the earth's radius by a factor of 4/3. Because the ray from source to receiver passes through not only the atmosphere, but also a considerable region beyond, the refraction is likely to be less than in ground point-to-point transmission. Since this effect depends on the rate of change of index of refraction with altitude, which in turn depends on geographic location and climate, there is some uncertainty in locating the radio horizon. This matter will be given further attention to determine what the refractive effect will be and whether or not it will be necessary to use special means to overcome its variability.

Because of doppler effect, the center frequency shift when observing a source on the satellite track will be positive and equal to $f(1 - \sqrt{\frac{v-c}{v+c}})$ when approaching the source and negative by an equal amount when leaving it (f = source frequency, v = S/C velocity, c = speed of light). At 3 GHz this amounts to $\pm$ 76 kHz.

d) Frequency Scanning

The basic relation limiting the rate of frequency scan is given
by equation (6). Although sine wave sources require a value of η in
that equation of about unity, some of the sources being measured may
resemble gaussian random noise when passed through the satellite receiver
bandwidth. For instance, a microwave relay for 600 voice channels
using FDM-FM will occupy a band of about 15 MHz. A filter looking at
a 1 MHz portion can be expected to see a gaussian process by the central
limit theorem. Based on the theory of estimation of gaussian noise
parameters (see e.g., Ref.41, p. 65), η in equation (6) should have
a value of about 70 to assure that the measurement error is less than
10% of the measured quantity.

Thus for a 1 MHz receiver bandwidth the frequency range scanned
in an interval as found in (22) is

$$F = \frac{B^2 T}{70} \simeq 3.0 \text{ GHz} \tag{23}$$

Further consideration may show that the high value of η of 70
is not required, permitting up to 10 GHz to be scanned using this
discipline.

Many of the signal sources will be pulsed radar with a low duty
cycle. Of course, scanning radars may not be pointing in the direction
of the spacecraft antenna when the latter is aimed at the radar. The
spatial dwell time of 0.21 seconds would have to be increased to guarantee
interception of a slowly rotating radar beam. In addition, if the two
antennas, radar and satellites are looking at one another and the satellite
receiver is sweeping in frequency, it must pass the radar frequency
at the time the radar pulse is emitted in order to be detected. For the
sweep rate of 2.86 GHz in 0.21 seconds, discussed above, the time any given
frequency is in the 1 MHz passband of the receiver is

$$\frac{0.21 \times 1}{3000} = 70 \text{ }\mu s$$

For a pulse repetition rate of 1000 pps, the probability of
detection on a single pass is only about 7% with corresponding results
for other repetition rates.

To improve the probability of detection, parallel scanning
receivers could be used, the bandwidth could be widened or the antenna
aperture made larger, permitting longer dwell times.

For example, with the 1° antenna, a bandwidth of 5 MHz, and
5 parallel channels, 1 GHz could be scanned and still one would be
certain to receive at least one pulse from a radar with a pulse rate
as low as 200 pps (0.2 seconds, dwell time). A scheme for doing this is
described in Appendix I.

3.3.2 Measurements Normal to the Earth

In this mode the antenna looks down to earth at the nadir. For h = 250 mi each degree of antenna beamwidth will intercept 4.36 miles of earth's surface so that for beamwidths ranging from 1.6^O to 3.2^O (which is the range of beamwidths of a 10 foot dish operating in the range of 2-4 GHz), the distance covered on the ground will range from 7 to 14 miles across. The rate of travel of the spacecraft is about 4.75 miles/s, so that a given point on the ground is cov··d for 1.47-2.94 seconds. The dwell time here is therefore greater than is for the circular horizon sweep and it will be possible to do the frequency scanning just as it was proposed for the circular sweep. There is sufficient time, in fact, to do a lateral sweep of several beamwidths.

For a spatial dwell time of 0.21 seconds discussed in connection with the circular sweep, 7 lateral aperture widths can be covered in the 1.47 seconds (corresponding to 1.6^O beamwidth) resulting in a total width close to 50 miles. At 3.2^O beamwidth, 200 miles could be covered. For this small scanning range mechanical scan should be feasible.

3.3.3 Sensitivity

Using the parameter values proposed in paragraphs 3.3.1 and 3.3.2, the sensitivity of each of the proposed techniques can be obtained from Fig. 15. In the case of horizon scan the parameter ℓ is about 25 miles (40 km) for a 1^O aperture. For a receiver sensitivity (kT_eB) of 10^{-14} watts this would provide an $EIRP_{min}$ of about 10^{-2} watts at 3 GHz. For the same antenna in vertical scan, the value of ℓ is 4.36 mi (7 km) with an $EIRP_{min}$ of 5×10^{-4} watts at 3 GHz. Lower receiver bandwidths (here assumed to be 1 MHz) would decrease these levels of $EIRP_{min}$.

To put these results in more specific perspective, estimates of received signal-to-noise ratios are made assuming some typical ground based sources. The calculations assume that the main lobes of the ground and space borne antennas are lined up. Of course, if the space-borne antenna were to look at side or back lobes, the received signal-to-noise ratio would be smaller. Typical antennas will have main lobe to side lobe ratios of 20 to 40 dB.

(a) Microwave Relay Source

Assume a microwave relay transmitter on the ground operating at 2000 MHz, generating 15 watts over a band of 15 MHz. The antenna is a 10 ft dish and is observed from a spacecraft at 250 mile altitude looking at the horizon. The distance between the two is about 1400 miles. The satellite receiver is assumed to have a bandwidth of 600 kHz, a noise figure of 10 dB, and a 10 ft diameter antenna. Thus:

Power transmitted = 42 dBm
Estimated loss in transmitter feeders = 5 dB
Receiver antenna gain = 34 dB

Transmitter antenna gain = 34 dB
Free space loss = 166 dB
Received power = 42 + 34 + 34 - 5 - 166 = -61 dBm
Noise power available = kTBF = -174 + 10 + 58 = -106 dBm

Received power in 600 kHz band = -61 + $\dfrac{600}{15,000}$ dB = -75 dBm
SNR = -75 - (-106) = 31 dB

Thus, the microwave relay main beam will be readily visible at the spacecraft but the relay may not be seen if an aspect well off axis obtains.

(b) Radar Source

Assume an S-band radar at 3 GHz, generating one microsecond pulses with a peak power of 0.5 MW. The antenna is a 15 ft dish. The spacecraft system is as given in (a) above except that the bandwidth is 5 MHz. The parameters here too are typical; the receiver bandwidth has the value chosen in Section 3 for the IF bandwidth used for observing radar emissions. Thus:

Peak power transmitted = 87 dBm
Estimated transmitter feeder loss = 5 dB
Transmitter antenna gain = 40 dB
Receiver antenna gain = 37 dB
Free space loss = 170 dB
Receiver peak power = 87 + 40 + 37 - 5 - 170 = - 11 dBm
Noise power = kTBF = -174 + 67 + 10 = -97 dBm
SNR (= peak signal power/noise power) = -11 - (-97) = 86 dB

Suppose that the satellite receiver were to look simultaneously at a microwave relay transmitter generating 10 watts in a 15 MHz band. The source antenna is 10 feet. To the observation being made of the received radar signal, this source would look like an additional gaussian random noise and we will treat it as such. The unwanted received signal power is obtained as follows:

Transmitter power = 40 dBm
Estimated feeder loss = 5 dB
Transmitter antenna gain = 37 dB
Receiver antenna gain = 37 dB
Free space loss = 170 dB
Total received power = 40 + 37 + 37 - 5 - 170 = -61 dBm
Unwanted received power in 5 MHz band = 61 + (1/3)dB = -66 dBm
SNR(= peak signal power/unwanted power) = -11 -(-66) = 55 dB

Even with a microwave source simultaneously present, the radar signal received will be high. Thus, for measuring radar the output of the receiver circuits should be clipped to eliminate the baseline noise associated with internal noise and with unwanted continuous emissions arriving from the ground.

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The emissions from radars off the center frequencies are substantial. As we have seen, the spurious emissions may be as high as 100 watts. Assuming this to be a peak power, one would therefore see 20-87 = -67 dB relative to the center frequency peak power. Assuming no substantial change in antenna gains and space loss at the spurious frequency as compared to the center frequency, the received SNR suffers by 76 dB to give an SNR of about 9 dB. This is not very high, but one would expect to be able to see it above the internal noise.

3.4 Antenna Systems

In the frequency interval 400-1000 MHz the antenna size required to achieve a 3^0 beamwidth is approximately 15 meters on a side. When looking vertically it would see about 13.2 miles at the low end of the band. For observations of noncoherent urban noise it would be more desirable to see a smaller region, from 3 to 6 miles, in which case the antenna would have to be at least twice as large. High resolution will clearly be difficult to achieve since such large structures are costly and involve problems of assembly in space. The millimeter wave experiment may also require the use of a large antenna and consideration should be given to shared use.

In view of the problem of size and cost of making measurements at the low end of the UHF band, a study has been initiated on means for achieving the required antenna properties as efficiently as is possible through the use of arrays.

The conventional approach is to arrange elements over an area with linear dimension as given above with regular spacing, at most, equal to one-half wavelength. For the frequency range given, this means an array with 20 elements on a side or a total of at least 400 elements. An array so constructed is called a filled array. The element spacing of one-half wavelength or less is required if the array is not to have multiple beams of equal gain known as grating lobes.

The number of elements calculated above may be impractical and alternatives are being sought. One possibility is to randomize the element locations. By destroying the periodicity of element placement the multiple lobes can be made to disappear but the effect is actually one of smearing out all but the main lobe; the peak sidelobe level is decreased but the average remains essentially unchanged.

In addition, if the beam steering feature is also desired, the overall system should include equal numbers of programmable phase-shifters and associated controlling circuits. It is therefore logical to look for other means of implementing this task.

A dramatic reduction in the number of elements for a given performance occurs when the radiation source is spatially incoherent.

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Use can then be made of the radio version of the Van Cittert-Zernike theorem in optics, which states that the mutual coherence function of the field from a spatially incoherent source is the Fourier transform of the intensity distribution of the source. In addition, the spatial coherence function for such sources is stationary in space.

Antenna elements are so located as to make the set of vector spacings between all possible pairs of elements identical to the set of vectors of uniformly distributed points on a planar surface. With no repetitions in vector spacings, N elements of the actual array can represent N(N-1) points on this surface. To realize a two-dimensional equivalent array, the elements should be located on a T or Y base, with most elements clustered around the junction. Only a few elements have to be located at the farthest points. This fact permits realization of equivalent array sizes far in excess of the actual extent of the spacecraft by placing a few elements on arms stretched out of the spacecraft.

Processing involves multiplication and integration of the outputs of every pair of elements in the array. Signal bandwidths are limited to about 1 MHz. Integration should be performed for about 0.1 seconds, after which the procedure is repeated for the next frequency slot. The output of each integrator represents the real part of the mutual coherence function for the vector spacing concerned. The imaginary part may be obtained by shifting the phase of one antenna output and performing the foregoing steps. The outputs of the integrator matrix may be digitized and transmitted to a storage/processing unit on the space shuttle or on the ground. There is an advantage to sending the raw data to ground because, in this form, it has virtually no redundancy. The intensity and angular distribution of sources within each band of frequencies is obtained by inverse Fourier transforming the mutual coherence coefficients in the space domain.

In practice, one may use IF conversion of antenna pickups which facilitates the phase insertion and multiplication process. If unequal lengths of connecting cables are used between the multipliers and antenna elements, allowance should be made for signal phase-shifts in them.

An interesting feature of this system is its capability of successive elimination of strong sources when trying to map more feeble radiations. The technique is analogous to adaptive nulling in adaptive arrays.

The frequency intervals beyond 1 GHz are adequately covered using relatively small parabolic dishes. Table 9 shows the gain and beamwidth range for parabolic dishes we may expect to use in the frequency intervals of interest here. (See also Fig. 17.) At 1 GHz a beamwidth of 3° actually requires a 20 foot diameter parabolic dish. If indeed such a size is to be used, an unfurlable structure would be required.

Table 9

Suggested Antenna Characteristics

Frequency Range, GHz	Parabolic Antenna Diameter (Ft.)	Beamwidth Range	Gain Range (dB)*
1-2	10	$3.2^\circ - 6.4^\circ$	27.5 - 33.5
2-4	10	$1.6^\circ - 3.2^\circ$	33.5 - 39.5
4-8	10	$0.8^\circ - 1.6^\circ$	39.5 - 45.5
4-8	5	$1.6^\circ - 3.2^\circ$	33.5 - 39.5
8-16	10	$0.4^\circ - 0.8^\circ$	45.5 - 51.5
8-16	5	$0.8^\circ - 1.6^\circ$	39.5 - 45.5
16-40	2.5	$0.65^\circ - 1.6^\circ$	39.5 - 47.5

* dB above an isotropic radiator with 0.54 efficiency

Current thinking is that the antenna diameter should be limited to 10 feet even in the 1 to 2 GHz interval. The sacrifice in resolution does not appear to be critical. At the low end of this band, one sees the long range radar systems which are widely dispersed geographically. Furthermore, antenna gain is hardly an important consideration for these systems. At the upper end of this band the beamwidth will be close to 3°, giving the desired resolution to the lower powered inhabitants of this region.

The 400-1000 MHz antenna system, if it is indeed to be a processed array, will be fixed in position and beam positioning would be done as part of the processing operation. For the frequencies above 1 GHz where the parabolic dish is proposed, scanning and positioning may be done electronically using multiple feeds, or it may be done with fixed feeds positioning the entire antenna. Since one mode of proposed operation involves 360° rotation of the beam, it appears reasonable to recommend a mechanical positioning system in which the entire antenna is moved. As envisioned now most of the data would be collected with the antenna (a) stationary and nadir looking, and (b) with the antenna looking to the horizon and rotating. In order to cover more territory in the nadir position, it is desirable to incorporate a scanning capability perpendicular to the direction of motion, as discussed in section 3.3.2.

In addition, it would be useful to incorporate a manual pointing facility which will enable the astronaut to focus on a source and follow it as the satellite passes by. In this way, partial radiation patterns of sources would be measured, providing a basis for extrapolating measurements in space to levels observed in aircraft, and perhaps on the ground as well.

Polarization of the sources being measured has been mentioned in earlier experimental proposals as information worth obtaining. The justification has not yet been explored but it is reasonable at this stage to ask that the antenna be designed to respond to orthogonal linearly polarized waves and to incorporate combiners which will make the antenna circularly polarized in either sense.

3.5 Hardware Implementation

The problems of hardware implementation considered so far are limited to questions of feasibility. Basically, no significant difficulty is anticipated in the development of a suitable sweeping receiver. A receiver developed by the National Scientific Laboratory [29] is designed to cover the frequency range 0.4 to 12.4 GHz. Its sweeping mode differs from the one recommended here but this does not constitute a fundamental difficulty. The dynamic (amplitude) range achieved is stated to be 65 dB minimum. The amplitude range requirement has not yet been fully considered but indications are that the range of amplitudes will be about 85 dB suggesting that the present capability may need to be extended. The receiver uses a YIG tuned preselector filter over part of its range and achieves 6 dB noise figure in the range 0.4 to 1 GHz and 10 dB in the range 1 to 12.4 GHz. This would be adequate though any improvement here

would be useful. With 6 dB noise figure the effective input temperature is about 1200 K. When measuring urban incidental noise, brightness temperatures of several thousand Kelvins are typically observed.

Though no thorough search has been made of off-the-shelf hardware, spectrum analyzer manufacturers can supply equipment for the frequency range of interest, with dynamic range quoted as high as 100 dB and with noise figure at the low end of the frequency range of 5 dB.

The possible need for using parallel channels in a sweeping receiver, as discussed in paragraph 3.3.1, may require special consideration. For example, one might use a multiple output oscillator and the various available output frequencies could be selected one at a time to give the required sweep. The feasibility of this procedure has not yet been explored.

3.6 Data Handling

The problems to be dealt with in the category of data handling include: (1) data processing on board the satellite and on the ground, (2) data storage requirements on the satellite and on the ground, (3) rates for transmission directly to earth stations and through the tracking and data relay satellite, and (4) methods of user accessing of the data. Should the antenna array be used as discussed in section 3.4, array processing would be required and this would most likely be better done on the ground.

Analysis of the precise requirements and development of techniques is planned during the coming phase of the project. The results will depend on whether or not parallel surveys will be made in different frequency bands or in different scanning modes, which depends in turn on how much payload can be devoted to the experiment. Other factors will influence the data requirements such as: the formatting scheme used; amplitude quantization required; frequency, time and location information required, etc.

For the method described in section 3.3.1 tentative data rates which will be useful at this stage for reference purposes can be established. For surveying continuous transmissions, the dwell time in each frequency slot is to range from 153 to 42 microseconds depending on the frequency band in use. Assuming $2^6 = 64$ amplitude steps for each measurement (measurements may be 1 dB apart giving a range of 64 dB), the highest rate needed is

$$6 \frac{bits}{sample} \bigg/ 42 \frac{\mu\ seconds}{sample} = 140\ k\ bits/s$$

For pulsed radar observations, the scheme devised makes 5 measurements in five contiguous bands in 5 millisecs. Assuming data are found in each band (it is likely that no more than two bands will contain information but estimates are made on the basis of all five and that peak amplitude, pulse repetition rate, and pulse width are each recorded in 6 bits, the data requirement is 18 k bits/sec, the radar measurement

needs are rather small. Both estimates assume there are data in every frequency slot and every frequency slot will be given a corresponding allocation of transmission time. If data are sparse, it is advantageous to transmit them with proper identification as to time of occurrence, location, and frequency, and to eliminate the slots containing no useful information. Whether or not this is done will depend on an analysis of the expected amount of data and an assessment of the overhead costs in attaching identifiers to the data as compared to the cost of retaining vacant slots. If the TDRS is used as a data relay to ground the requirements of information storage would be determined by the queuing discipline for the relay satellite. If data is relayed to gro 1 stations en-route, the storage requirements are determined by the time to travel between ground stations, time over the ground station, data rate capability of the satellite-to-ground link, etc. In this regard, an estimate of the data storage capabilities of magnetic tape is in order. Tape storage systems available today will accommodate 1600 bytes/inch (8 bits per byte) and can run at rates of 20 inches/second. Systems of this kind can therefore accept 216 k bits/second which is consistent with the earlier estimate of the rate with which data are being generated. 20 inches/sec. corresponds to 6000 feet per hour or about 9000 feet per orbit. Two to three reels of tape would typically be accumulated per orbit if, indeed, data are stored without pre-processing to eliminate redundancy. If the data are to be discharged to ground stations, means will have to be provided for rapid playback during the brief overflights of the ground stations.

A problem which will have to be faced is concerned with the correct location of an emitting source. Because the satellite antenna is not able to totally reject signals off the main beam, one must expect large amplitude sources to develop a significant output wherever they are relative to the satellite antenna angle. In particular, a rotating source in the annulus discussed above is more likely to have its main lobe looking into the satellite antenna sidelobes or back lobes than into its main lobe. Readings obtained in such cases might be assumed incorrectly to come from the direction of the satellite antenna main lobe. A possible solution to this problem is to examine successive frequency sweeps since the measurements in successive sweeps are made with the main lobe of the satellite antenna in another, adjacent, location. If the reading at a given frequency changes in conformity with the shape of the main lobe gain the target is on the main lobe, otherwise it is likely not to be. Thus, signal processing, along with better than usual main lobe to back and sidelobe ratios, may solve the problem.

4.0 SUMMARY AND FUTURE EFFORT

A plan has been outlined for systematically surveying the electromagnetic environment on earth from a satellite platform on the space shuttle. The basic modes of spatial scanning are: (1) a scan looking nearly vertically to the ground advancing along the satellite track and scanning laterally to distances of up to ± 100 miles from the center of the track, (2) a circular scan looking to the horizon sweeping a spiral annulus over the earth's surface, (3) a manual or automatic track scan for tracking individual sources. The first mode will give information on levels radiated directly upward into space and the second mode will give information on emissions tangent, or nearly tangent to the earth's surface. The third mode will provide information on the angular emission pattern of sources so investigated.

Attention was given to three major kinds of emission waveforms expected as follows: (1) incidental emissions arriving from many noncoherent sources, (2) intentional continuous wave broadband emissions, and (3) intentional pulsed low duty cycle emissions.

A preliminary examination of hardware feasibility and data rate requirements does not reveal any major area of difficulty except for the low frequency (0.4-1.0 GHz) antenna. Sweeping receivers are currently available for the range of frequencies of interest (0.4-16 GHz) and estimated data rates are such as could be accommodated directly on digital tape. To deal with the problem of the low frequency antenna, a study has been initiated aimed at establishing the feasibility of a sparse array which will give the necessary spatial resolution.

The continuing study will:

1) Investigate user requirements for data on frequency, amplitude, polarization, modulation, etc. The principal users are NASA, the Electromagnetic Compatibility Analysis Center, The Federal Communications Commission, and the Environmental Protection Agency.

2) More accurately determine the scanning system parameters accounting for second order effects such as refraction.

3) Determine the degree of coverage achieved in a flight of specified duration.

4) Determine the probability of missing given sources.

5) More accurately estimate fields in space.

6) Determine whether or not parallel measurements covering more than one frequency band or scanning mode are feasible or desirable.

7) Determine additional hardware parameters such as dynamic range and spurious response rejection.

8) Develop the data handling techniques including processing for redundancy removal, storage, transmission, and information processing

9) Continue the low frequency antenna analysis.

10) Estimate requirements for power, size and weight.

11) Plan the various flights.

For the last item, information will be needed from items (3), (4), and (6) on the degree of coverage and probability of seeing sources in a flight of specified duration and on the possibility of parallel measurements.

5.0 REFERENCES

1. V.F. Henry and J. J. Kelleher, "Radio Frequency Interference Experiment Design for the Applications Technology Satellite," NASA TN D-5041, May 1969.

2. K. H. Hurlbut and C. J. Zamites, "Electronics Program: Radio Frequency Interference at Orbital Altitudes," Report No. TDR-269 (4250-44)-2, October 1964.

3. H. K. Mertel, "Feasibility Study of Man-Made Radio Frequency Radiation Measurement," NASW-1437, Convair Div., General Dynamics Corp., Aug. 1, 1966.

4. "Study of Existing and Planned Radio Interference and Propagation Program (RIPP) Experiments," NAS 5-11835, Modification 27, National Scientific Laboratories, Inc., March 1972.

5. "A Report on a Study for the Inclusion of a Radio Frequency Interference Experiment on an ITOS-D Series Spacecraft," AED-R-3906F, RCA Corporation, January 1973.

6. "Feasibility Study of Man-Made Radio Frequency Radiation Measurements from a 200-Mile Orbit," General Dynamics, Convair Div., Feb. 1967.

7. W. W. Ward et. al., "The Result of the LES-5 and LES-6 RFI Experiments," TN-1970-3, Lincoln Laboratory, MIT Lexington, Mass., Feb. 1970, AD 703 738.

8. W. W. Ward, et. al., "The Results of the LES-5 and LES-6 RFI Experiments," TN-1970-3, suppl-1, Lincoln Laboratory, MIT, Lexington, Mass., July 1970, AD 709 766.

9. K. H. Hurlbut and C. J. Zamites, "UHF Radio Frequency Interference Measurements at Synchronous Altitudes," TR-0066 (5230-01)-1, Aerospace Corp., El Segundo, Calif., January 1970, AD 703 712.

10. J. R. Herman and J. A. Caruso, "Radio Astronomy Explorer (RAE)1 Observations of Terrestrial Radio Noise," NASA-CR-122401, Analytical Systems Corp., Burlington, Mass., October 1971, N72-24165.

11. Bergman, Rice, and Miles, "Mathematical Computer Model and Predictions for ATS-F Radio Interference Experiment at 6 GHz," COM-72-11409, Office of Telecommunications, Boulder, Colo., August 1972.

12. R. E. Taylor, R. E. Prince, and D. N. McGregor, "A Shuttle/Spacelab RF Environment Survey Facility," Paper 14B, Natl. Telecommunications Conf.(NTC-74) Dec. 2-4, 1974, San Diego, Ca.

13. S. E. Scrupski, "Users Starting to Hop Aboard U.S. Communications Satellites," Electronics 95, 3 October 1974.

14. "Space Shuttle RFI Experiment Study,"Interim Report, Operations Research, Inc., Silver Spring, Md., 22 July 1974.

15. H. K. Mertel, "Feasibility Study of Man-Made Radio Frequency Radiation Measurements from a 200-Mile Orbit," Report No. ZZK 67-007, Convair Div., General Dynamics, San Diego, Calif., Feb. 1967.

16. G. Ploussios, "Noise Temperature of Airborne Antennas at UHF," Technical Note 1966-59, Lincoln Laboratory, MIT, Lexington, Mass.,6 Dec. 1966.

17. A. H. Mills "Measurement and Analysis of Radio Frequency Noise in Urban, Suburban, and Rural Areas," NASA-CR-72490; GDC-AWV68-001, Convair, San Diego, Calif., February 1969, N69-18667.

18. A. H. Mills, "Measurement of Radio Frequency Noise in Urban, Suburban and Rural Areas," NASA-CR-72802; GDC-AWV70-001, Convair, San Diego, Calif., Dec. 1970, N71-14754.

19. G. Anzic and C. May, "Results and Analysis of a Combined Aerial and Ground Ultrahigh Frequency Noise Survey in an Urban Area," NASA-TM-X-2244; E-6002, Lewis Research Center, Cleveland, Ohio, April 1971, N71-22623.

20. G. Anzic, "Radio-Frequency Noise Measurements in Urban Areas at 480 and 950 Megahertz," NASA-TM-X-1972, Lewis Research Center, Cleveland, Ohio, March 1970, N70-20688.

21. G. Anzic, "Aerial RF Noise Measurement in Urban Areas at UHF Frequencies," NASA-TM-X-52751, Lewis Research Center, Cleveland, Ohio, April 1970, N70-32673.

22. G. Anzic, "Measurement and Analysis of Radio-Frequency Indigenous Noise," 1970 IEEE International Symposium on Electromagnetic Compatibility Record.

23. C.R.W. Barnard, "VHF Noise Levels over Large Towns," Royal Aircraft Establishment, Tech. Report 67213, August 1967, AD 827-640.

24. W. E. Buehler, C. H. King, and C. D. Lunden, "VHF City Noise," 1968 Record of IEEE Electromagnetic Compatibility Symposium, pp. 41-51, January 1968.

25. E. N. Skomal, "Analysis of Airborne VHF/UHF Incidental Noise over Metropolitan Areas," IEEE Trans. on EMC, May 1969, p. 76.

26. E. N. Skomal, "The Range and Frequency Dependence of VHF-UHF Man-Made Radio Noise in and above Metropolitan Areas," IEEE Trans. on Vehicular Technology, May 1970.

27. C. J. Zamites and K. H. Hurlbut, "Measurements of Interference Levels in the UHF Band from Aircraft Altitudes," IEEE Trans. on EMC, Aug. 1970.

28. D. Madison, L. Kuehn, T. Bode, "Airborne European RF Measurements in the 100-500 MHz Band," ESD-TR-72-293, IIT Research Institute, Chicago, Nov. 1972, AD 758 772.

29. "RFI Experiment Definition Project Report," Report No. 74-N-003, National Scientific Laboratories, Inc., McLean, Va., June 1974.

30. Ward, Sicotte, Hurlbut, and Zamites, "The Results of the LES-5 and LES-6 RFI Experiments," Report No. TN-1970-3 ESD-TR-70-8, MIT, Lexington, Mass., 6 Feb. 1970, AD 703-738.

31. Ward, Sicotte, Hurlbut, and Zamites, "The Results of the LES-5 and LES-6 RFI Experiments," (supplement to report of 6 Feb. 1970), Report No. TN-1970-3-Suppl-1 ESD-TR-70-194, MIT, Lexington, Mass, 6 Feb. 1970, AD 703-738.

32. D.R.J. White, A HANDBOOK SERIES ON ELECTROMAGNETIC INTERFERENCE AND COMPATIBILITY, Vol. 3, EMI Control Methods and Techniques, Don White Consultants, Inc., Germantown, Md., 1973.

33. D. E. Cridlan, "Microwave Radio Relay Links: The Effects of Spurious Emissions from High-Powered Radars," Post Office Electrical Engineer's Journal, 82 (July 1969).

34. H. A. Myers, "Airborne Radar Signal Density Measurements," IEEE Trans. on RFI, 28 (June 1963).

35. FCC Rules and Regulations, Federal Communications Commission, Wash., D.C.

36. Broadcasting Radio Service Branch, FCC, Washington, D.C., Private Communication.

37. Cable Television Branch, FCC, Wash., D.C., Private Communication.

38. Common Carrier Branch, FCC, Wash., D.C., Private Communication.

39. MCI Telecommunications, Inc., Philadelphia, Pa., Private Communication.

40. CCIR Documents of the XIth Plenary Assembly, Vol. IV, Radio Relay Systems, Space Systems and Radio Astronomy, ITU, Oslo 1966.

41. R. F. Ficchi, Ed., PRACTICAL DESIGN FOR ELECTROMAGNETIC COMPATIBILITY, Haydon Book Co., New York, 1971.

Appendix I

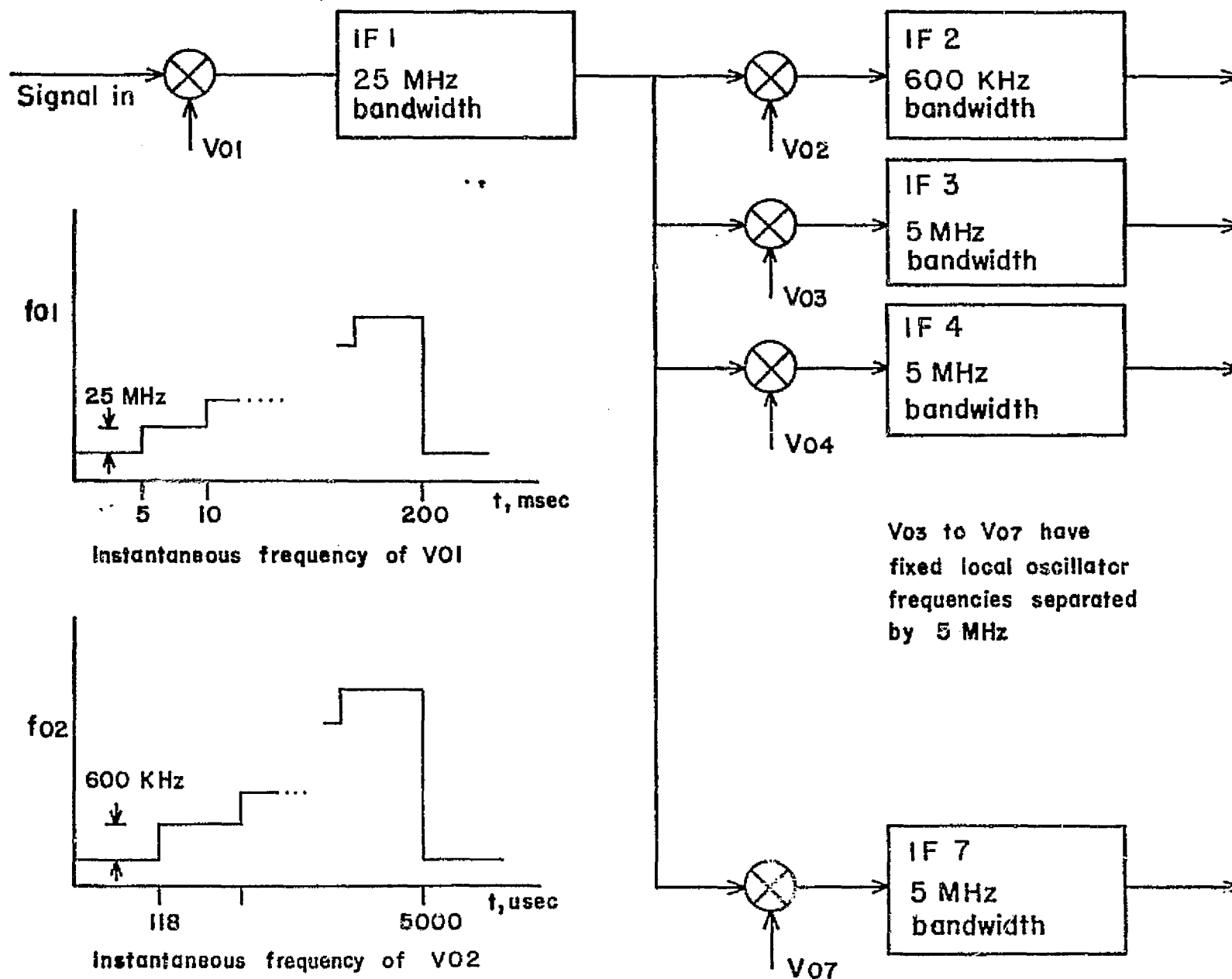## A SCANNING RECEIVER FOR PULSED SOURCES

Detecting pulsed RF sources such as radars demands special consideration. If the two antennas, radar and spacecraft, are looking at one another and the spacecraft receiver is sweeping in frequency, it must pass the radar frequency when a pulse is being emitted in order to detect it.

We can view the scanning process as taking place in steps, with the receiver filter center frequency being stepped periodically by an amount equal to the receiver IF amplifier bandwidth. When the pulse occurs it encounters one of the receiver filters which may or may not be centered on or near the pulse radio frequency. Assume, for instance, that we are searching the 1-2 GHz band where many radars will be found. If we are to search the entire band in 0.2 sec, equation (23) shows that we will need a bandwidth of at least 591 kHz. Using this bandwidth, each bandwidth increment would be observed for about 118 microseconds. If the pulse repetition rate is 1000 pps, pulses occur at intervals of 1 millisecond and the probability of a pulse falling exactly into the filter corresponding to its center frequency is about 10%. At higher frequencies where the bandwidth prescribed by equation (23) is larger, the frequency dwell time is smaller, and the probability of encountering a pulse is even smaller. To insure interception, the technique of ubiquitous spectrum analysis may be used in conjunction with conventional scanning. Most radars are found in the range of 1-4 GHz and repetition rates are generally higher than 200 pps, or have pulses at most 5 milliseconds apart. If we allow T_a to be at least 5 milliseconds, at least one pulse will be encountered. In a spatial dwell time of 200 milliseconds there are forty 5 millisecond intervals and in each we will examine 1/40 of the total range. For the 1-2 GHz range this means examining 25 MHz at a time. To get an acceptable frequency resolution the 25 MHz band may be examined in a bank of five contiguous filters each of a bandwidth of about 5 MHz. Each of these sub-bands of 5 MHz would be examined for 5 milliseconds and sometime during this interval one or more pulses would occur if the sub-band corresponds to a frequency at which the pulse has significant energy. For the 2-4 GHz range, 50 MHz would be examined at one time. Five sub-bands, each of 10 MHz bandwidth, would cover this range, yet keep the sub-band filters to a reasonable number.

A block diagram of the receiver for the 1-2 GHz band is shown in Fig. A-1. It is arranged to do a conventional scan in discrete steps in a band of about 600 kHz looking in each band for 118 microseconds. At the same time it will examine forty 25 MHz bands, observing each 5 MHz sub-band for 5 msec. While the entire 25 MHz IF filter output could be examined without going to the sub-bands, using the technique shown will reduce the noise level.

Receiver for 1-2 GHz band   FIGURE A-1

Instantaneous frequency of VOI

Instantaneous frequency of VO2

IF I
25 MHz
bandwidth

IF 2
600 KHz
bandwidth

IF 3
5 MHz
bandwidth

IF 4
5 MHz
bandwidth

IF 7
5 MHz
bandwidth

Vo3 to Vo7 have
fixed local oscillator
frequencies separated
by 5 MHz

The 5 MHz filters have sufficient bandwidth to accept most radar pulses without distortion and the observation interval is enough to allow two or more pulses to show up. This assertion is based on the observation that the predominant L-band radars used for air traffic control have pulse widths of 2 microseconds at a repetition rate of 350 pps and the predominant S-band radars have a pulse width of 0.8 microseconds at a repetition rate of 1200 pps. The 5 MHz filter described here can accept pulses as short as 0.2 microseconds at repetition rates as low as 200 pps. This suggests that each interval can be used to give peak received pulse power and time between pulses or repetition rate. As a rule only one of the 5 MHz filters will pass the pulses, though two adjacent filters may sometimes share the spectral energy of the arriving pulses. In rare cases non-adjacent 5 MHz filters may contain output information suggesting that more than one source is in view of the receiving antenna. Depending on the results of a survey of frequency assignment, we may ultimately recommend that data from only one of the five filters be passed on to the recording apparatus.

The 5 MHz filters may also see non-radar sources which, if they occur, will usually give rise to a low level noise-like background. Since these channels are being included specifically for recording pulsed radar, it is advisable to design the measuring circuit so that it requires a minimal level in order to respond.